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CONSIDERATIONS TOWARD THE SELECTION OF AN ELECTRICAL POWER SYSTEM FOR THE LOGISTICS SPACECRAFT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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CONSIDERATIONS TOWARD THE SELECTION OF AN ELECTRICAL POWER SYSTEM FOR THE LOGISTICS SPACECRAFT

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CONSIDERATIONS TOWARD THE SELECTION OF AN ELECTRICAL POWER SYSTEM FOR THE LOGISTICS SPACECRAFT

SUMMARY

This paper presents the analysis and considerations which result in the tentative selection of a fuel cell-battery combination power system to supply electrical power for the Space Station Logistics Spacecraft. The storable propellant reciprocator-battery system and the all-battery system may also be used at a weight penalty. A combination water evaporation and radiator system is selected for thermal control.

The power systems selected for analysis are either partially developed or have a reasonable chance of development in sufficient time for this mission. Reliability and minimum weight are significant bases for power system selection; low volume is also important but is a less significant goal. Growth potential and cost are also considered.

Several power system configurations are treated to determine which will yield minimum weight with adequate redundancy. The configuration selected has consummables and batteries located in both modules with the power conversion unit located in the crew module. The problems of storing hydrogen and oxygen for long periods in space and of thermal control of the power system are treated.

INTRODUCTION

The selection of a space power system for a manned space flight mission must be sensitive to all pertinent aspects of the specific mission, the function of the crew, and the spacecraft configuration. The power systems must be compatible with mission requirements such as long-term storage in space and available energy sources suitable for the duration of the mission.

The studies performed in this paper represent the combined analysis of power systems and related chemical storage, thermal control, and other subsystems which must be considered in order to select an electrical power generation system for this mission. The combined study is mandatory since limitations on the storability of cryogenic propellants influence the choice of the energy source, and since limitations of the thermal control system may drastically influence the types of power systems considered. Consideration is also given to such factors as development status, reliability, weight and growth potential.

The power requirements of a twelve-man, lifting reentry, horizontal landing type Logistics Spacecraft are presented. Both chemical and radioisotope energy sources are considered. Thermal control by radiative and evaporative systems are treated.

MISSION DESCRIPTION AND SPACECRAFT CONCEPTS

Mission.- The Logistics Spacecraft shall be capable of transporting cargo and twelve crew members to and from a manned, earth-orbiting space station and shall provide for reentry, landing and recovery. The recovered spacecraft shall be suitable for reuse.

Guidelines.- The technical guidelines pertinent to this study may be summarized as follows:

1. A one orbit abort recall capability for maximum crew safety shall be practicable.

2. Maximum recycling or refurbishment of systems must be realized.

3. Single mission operational life shall be 48 hours with a 90 to 180 day orbital storage interruption following the first 24-hour operational period.

4. The crew module shall provide a habitable environment for a period of at least one day after landing.

Configurations.- Two configurations for the Logistics Spacecraft are being studied under contract from MSC: The blunt body or ballistic reentry type; and the lifting reentry, horizontal landing type. The spacecraft is comprised of two modules, the forward or crew module and the cargo module. The latter also serves as an adapter. This cargo module shall be capable of ferrying liquid and solid supply items and shall be non-recoverable.

The lifting reentry configuration has been selected for this study because it has the added requirement of hydraulic power for movable control surfaces during reentry. The power systems for the ballistic reentry type and lifting reentry type should be essentially the same excape for the hydraulic power. The thermal control system may be slightly different as a result of configuration differences.

Locations of Power Systems.- This study considers a variety of power system types. Each system is considered in combination with batteries for peak power and emergency conditions. It is assumed that the primary power generation system, including tankage, reactants, and cooling equipment, may be located in either the cargo or crew module with consummables and batteries stored in either or split. Hydraulic pumps for control surface actuation are located in the crew module.

Location of the power system may be dictated by weight and volume limitations or by center of gravity requirements. Staging of the adapter module just prior to reentry demands that reentry and post-landing power be supplied from systems located within the crew module. Table I lists the system configurations considered in this study.

Electrical Power Profile.- Since the power requirements of the Logistics Spacecraft are estimated to be similar to those of Gemini, except for an increased environmental control requirement and the addition of hydraulic power, a Gemini power profile was modified to determine the power and energy requirements. This power profile is presented as figure 1 and represents a mission in which all parking orbit allowance is utilized. The total combined energy is 150 kw-hr. The design power level for fuel cells or dynamic systems is 2.1 kw; peaks before reentry are 4.6 kw. A reentry peak of 12.4 kw is required by hydraulic actuators for the maneuvering control surfaces.

Figure 2 represents the energy required for "perfect" launch and rendezvous and "perfect" separation, reentry, and landing. In other words, if a launch is made at the optimum time for rendezvous with the Space Station, no parking orbit would be required for phasing and only three hours would be required to arrive and dock. This represents 14.1 kw-hr of energy, and batteries would be included to ensure that this energy is always available. Likewise, if separation occurs at exactly the proper time for landing in the designated spot with no parking orbit for phasing, only 3.5 hours would be required to separate, reenter and land. This represents 15.3 kw-hr and would also be provided by batteries. Postlanding energy requirement would remain at 20.3 kw-hr.

Figure 3 shows the energy blocks used for power system design. As previously stated, fuel cells and dynamic engines are considered to be designed for outputs of only 2.1 kw. Any load above 2.1 kw is considered to be a peak and will be handled by batteries. The only exceptions to this are where turbines and the hypergolic reciprocator are assumed to be designed to take peak loads. Enough batteries are provided to supply minimum launch and rendezvous power and minimum reentry and landing power plus peaks. In some cases the 20.3 kw-hr post-landing requirement is also furnished by batteries.

ANALYSIS OF ELECTRICAL POWER SYSTEMS

Selection of Power Systems for Analysis

The power systems selected for analysis are either partially developed or have a reasonable chance for development in sufficient time for this mission. Reliability and minimum weight are significant bases for power system selection; low volume is also important but is a less significant goal. Growth potential, development time and cost are also considered.

The following power systems types are selected for analysis:

1. Primary batteries
2. Hydrogen-oxygen (H_2-O_2) fuel cells
3. Storable reactant fuel cell
4. Storable monopropellant turbine
5. Storable bipropellant (intermittent) turbine
6. Storable bipropellant (hypergolic) reciprocator
7. Hydrogen-oxygen reciprocator
8. Hydrogen-oxygen Stirling cycle reciprocator
9. Hydrogen-oxygen Brayton cycle turbine
10. Isotope - Stirling cycle reciprocator
11. Isotope - Brayton cycle turbine
12. Isotope - Rankine cycle turbine

Energy Source.- Power generation systems for space applications may utilize three energy sources: solar, nuclear (reactor or radio-isotope), or chemical. The majority of the above selected systems utilize chemical energy since these systems are relatively lightweight and operate efficiently for low power, short duration missions. A variety of chemical systems are currently under development which utilize hydrogen and oxygen, Aerozine-50 and nitrogen tetroxide, monopropellant hydrazine, or combinations of these. The remainder of the systems selected for this analysis utilize radioisotopes as the heat source. The isotope can be produced in a cylindrical form which can easily be integrated in heat exchangers for utilization with power systems. Most probable isotopic sources for the subject mission are Polonium-210 or Plutonium-238 with half-lives of 138.4 days and 86.4 years, respectively. These alpha-emitting sources are the least hazardous of the isotopes actively considered for space power applications.

Solar and reactor energy sources were excluded in the system selection process. Solar conversion devices were rejected due to the large exposed areas required to intercept a sufficient quantity of solar radiation and due to their strict orientation requirement. Also, rendezvous and maneuvering requirements prevent the use of a solar energy conversion system. Another disadvantage of solar conversion systems is the need for energy storage devices to provide energy during the shadow portion of earth orbits. The reactor energy sources were rejected due to excessive weight required for shielding against harmful radiation. Also, associated development time and costs for reactors for the specific power level of the Logistics Spacecraft are prohibitive.

Chemical Storage.- Two general types of chemical fluids are considered in this study, the earth storables such as hydrazine and nitrogen tetroxide, and the cryogenics - hydrogen and oxygen. As their name implies, the earth storable fluids can be stored indefinitely with minimum restrictions on temperature and pressure. Tankage utilizing bladder expulsion techniques are in current usage for space vehicles.

There have been considerable questions raised, however, over the long-term storability of hydrogen and oxygen. For the Logistics Spacecraft, this is of particular interest if these cryogenic fluids are to be utilized after the six-month orbital storage period. Analysis has shown that it is impractical to store cryogenic oxygen and hydrogen inactively for as long as six months in space. This can be done with high pressure gas storage with considerable weight savings and with a reasonably small volume penalty above that required for supercritical storage.

Power Conditioning.- A power split of 60 percent d-c, and 40 percent a-c is assumed, based on Apollo experience. If the power system generates all d-c, this output is passed through a regulator weighing about 7.5 lb/kw and that portion required for a-c is passed through an inverter weighing 32 lb/kw. If the system generates a-c, all power is regulated at a penalty of approximately 7 lb/kw; the a-c power is further passed through frequency changing equipment weighing about 20 lb/kw to get the assumed 400 cps output, and that portion required for d-c passes through a transformer - rectifier weighing approximately 15 lb/kw.

A cable weight of 20 pounds for the power conditioning system was assumed. The total power conditioning weights are listed in table II.

Thermal Control. - A preliminary thermal control analysis is presented as appendix A. Heat rejection by radiators, fluid evaporation systems, and combinations of these two are considered for five typical power systems. This analysis is preliminary and is intended only to indicate trends. Also, some of the assumed heat rejection requirements have changed since the writing of the appendix. These changes, however, have been incorporated in the weight estimates. System cooling weights are based primarily on an all-radiator system, and credit is given to systems which produce water for cooling or drinking purposes. Water boilers are included where practicable to ensure adequate heat rejection for the 3-hour and 3.5-hour minimums of figure 2.

Since water evaporators offer redundancy for a small weight penalty they may be included to backup the radiator system. It is recognized that a combination radiator and water evaporation system offers possibility of weight savings, but a more detailed thermal control analysis would be required to establish these weights precisely.

Conversion System Characteristics. - As previously stated, twelve power systems are selected for potential applicability to this mission. System weights are presented in table I and figure 4. A brief description of their characteristics follows:

1. Primary batteries: Batteries are a low volume, modularized, low cost, reliable source of power and are at a very high state of development. Present day batteries can yield 80 w-hr/lb and the technology is advancing. Battery temperatures must be maintained between 60° F and 160° F for efficient operation. They may be used either as the primary power source, as in Mercury, or for peak and emergency power.

For the Logistics Spacecraft, either preflight activated (already charged with electrolyte) or remotely activated batteries may be utilized. Precharged batteries have higher energy densities but shorter shelf life after activation. They must be trickle-charged continuously to maintain their capacity during storage. Remotely activated batteries have a longer inactivated storage life (3-5 yr) but a lower energy density (40-65 w-hr/lb). The electrolyte is forced into the cell by firing squib valves just prior to use.

Since provisions already are made for the Space Station power system to supply a trickle-charge, the 80 w-hr/lb batteries will be used in the weight estimates. However, at a later date the longer storage life of the remotely activated batteries may be more attractive.

2. H_2-O_2 fuel cell: Several types of hydrogen-oxygen fuel cells are currently under development; however, only three are considered here: The General Electric (GE) ion-exchange membrane type, the Pratt and Whitney (P and W) porous metallic electrode type, and the Allis-Chalmers asbestos electrolyte holder type. Each system operates on the same general principle in which chemical energy is converted directly into electrical energy with potable water and heat as by-products. The reaction is stoichiometric such that one part of hydrogen combines with eight parts of oxygen in producing the electricity. The heat sink capability of hydrogen is sometimes utilized for cooling purposes and excess hydrogen may be passed through the cell for this purpose. Primary advantages of fuel cells are their high efficiency and low fixed weight. Principal disadvantages are the need for cryogenic tankage and supplemental cooling.

a. GE fuel cell.- The operating conditions of this system are 100°-155° F at 20 psi. Operational temperature is limited by the characteristics of the polymer membrane. Waste heat is removed by a closed coolant loop and a space radiator. Specific reactant consumption is approximately 0.9 lb/kw-hr and thermal efficiency is approximately 56 percent. This system is being developed for the Gemini spacecraft. Batteries would be employed to take peak loads above 2.1 kw in the Logistics Spacecraft.

b. P and W fuel cell.- This fuel cell may operate on either a closed or an open cycle using excess hydrogen for cooling in the latter case. Dual porosity nickel electrodes are used in conjunction with an aqueous potassium hydroxide electrolyte. Operation is at 60 psi and 450° F. Specific reactant consumption is approximately 0.8 lb/kw-hr at 68 percent thermal efficiency. This system is under development for Apollo and LEM. Again, peaking batteries would be used for peak loads on the Logistics Spacecraft.

c. Allis-Chalmers fuel cell.- This cell utilizes a capillary membrane and operates at 30 psi and from 190°- 210° F. It is comparable in many respects to the P and W cell. Its development is being funded by various government agencies.

3. Storable reactant fuel cells: Storable reactant fuel cells are in the initial development stage, although Allis-Chalmers has a unit operating successfully on hydrazine (N_2H_4) and oxygen (Note - The oxygen is not storable; it may be stored in pure form as a cryogenic fluid or as high pressure gas or it may be obtained from the decomposition of nitrogen tetroxide or hydrogen peroxide.) Several other storable reactant combinations are under investigation but only the hydrazine-oxygen cell will be considered here. The principle of operation is similar to that of the hydrogen - oxygen fuel cell.

The overall efficiency of the cell is 40 percent at 100 amps/ft^2. The specific propellant consumption (SPC) is approximately 2.26 lb/kw-hr. The principle advantage is the ability to utilize storable reactants.

4. Storable monopropellant turbine: This turbine power unit is being developed by Sundstrand and operates open cycle from the gases resulting from the decomposition of hydrazine. It can be either electrically or hypergolically* started and it produces both electrical and hydraulic power. This power unit is in advanced development, however, its present design is larger than actually required for the Logistics Spacecraft. SPC is approximately 5 lb/kw-hr.

5. Storable bipropellant (intermittent) turbine: The intermittent or pulse turbine operates open cycle and derives its energy from the results of the hypergolic combination of Aerozine-50 (50 percent N_2H_4 and 50 percent UDMH) and nitrogen tetroxide (N_2O_4). Combustion occurs in an external combustion chamber and the hot gases are pulsed through the turbine at approximately four second intervals to keep turbine blades below maximum temperatures. Initial feasibility has been demonstrated by Thompson-Ramo-Wooldridge on company funds; no further development of this system is underway. Expected SPC is around 6 lb/kw-hr.

6. Storable bipropellant (hypergolic) reciprocator: This engine is a single cylinder, liquid cooled, port exhausted reciprocator employing a two-stroke modified Otto cycle. The hypergolic combination of Aerozine-50 and N_2O_4 is injected through specially designed dual concentric mono-seat poppet valves near top dead center of each stroke. Burning at nearly constant volume at an oxidizer to fuel ratio of 1.8 is expected to yield a specific propellant consumption of 4 lb/kw-hr. This engine is being developed by The Marquardt Corporation under sponsorship of NASA-MSC. The apparent advantages of this system are operation on the same reactants used in many current propulsion systems and the possibility of utilizing the same tankage. Other advantages are simplicity and low fixed weight. Primary disadvantages are its relatively high propellant consumption rate and its external cooling requirement.

7. Hydrogen-oxygen reciprocator: Vickers Incorporated is presently under contract to NASA-Lewis to develop a single cylinder, single stage, reciprocating, internal combustion engine to operate on hydrogen and oxygen. A modified Diesel cycle is employed with controlled oxygen injection. Either a platinum catalyst or a spark plug is used for

*Hypergolic refers to the spontaneous combustion occurring when certain fuel-oxidizer combinations come in contact with each other.

starting the combustion process. SPC achieved to date has been 2.3 lb/kw-hr. Primary advantages of this system are simplicity and low fixed weight; disadvantages are the need for additional tankage for the cryogenic propellants and the external cooling requirement.

8. Hydrogen-oxygen Stirling cycle reciprocator: This reciprocator operates on the closed Stirling gas cycle utilizing neon or helium as the working fluid. This thermodynamic cycle consists of isothermal compression, constant volume heat addition, isothermal heat addition and expansion and constant volume heat rejection. Heat addition to the gas is obtained from the open cycle combustion of hydrogen and oxygen in an external combustor. This system is being developed by the Allison Division of the General Motors Corporation under Air Force contract and has reached a fairly high state of development. Primary advantage is high cycle efficiency; disadvantages are complexity and high reactant consumption of the combustor.

9. Hydrogen-oxygen Brayton cycle turbine: This system operates with a closed Brayton gas cycle utilizing an inert gas such as helium as the working fluid. This thermodynamic cycle consists of isentropic compression, constant pressure heat addition, isentropic expansion and constant pressure heat rejection. Heat is added to the gas by externally combusting hydrogen and oxygen. The system is characterized by high cycle efficiency but also by large radiator areas as a result of low temperature heat rejection requirements. Predicted reactant consumption in the combustor is quite high.

10. Isotope - Stirling cycle reciprocator: The conversion system is as described above; however, heat for this system is obtained from radioactive isotope decay. Possible location of the isotopes are in the engine head or in an external heat exchanger.

11. Isotope - Brayton cycle turbine: The conversion system is as described previously.

12. Isotope - Rankine cycle turbine: This system operates on the liquid-vapor Rankine cycle utilizing mercury or rubidium as the working medium. This closed cycle consists of isentropic pumping, constant pressure heat addition, constant temperature and pressure heat addition, isentropic expansion, and constant temperature and pressure heat rejection. The system is characterized by relatively low efficiencies but small radiators can be used due to the relatively high condensing temperatures.

SYSTEM SELECTIONS

System weights are consolidated in table I. The first five selections, based on minimum weight, are given below. An explanation of the selected configurations is outlined in appendix B.

1. Pratt and Whitney closed cycle hydrogen-oxygen fuel cell (1,396 lbs);

2. Allis-Chalmers hydrogen-oxygen fuel cell (1,530 lbs);

3. Allis-Chalmers storable fuel cell (1,554 lbs);

4. and 5. Marquardt's hypergolic reciprocator and General Electric's fuel cell (both weigh 1,793 lbs).

It is interesting to note that a single configuration resulted in the minimum weight for all three hydrogen-oxygen fuel cells. In this case the fuel cell would be located in the crew module along with a 20.3 kw-hr supply of high pressure reactants and 15.3 kw-hr of batteries. In the adapter would be housed the equivalent of 51.5 kw-hr of subcritically stored reactants for ascent, 43.9 hw-hr of high pressure reactants for descent, and 19.0 kw-hr of batteries for peaks, spikes, and minimum rendezvous power.

The configurations selected for the storable fuel cell and the hypergolic engine systems had the fuel cell or engine in the crew module with 20.3 kw-hr of reactants and 15.3 kw-hr of batteries. In the adapter would be located 95.4 kw-hr of reactants and 19.0 kw-hr of batteries. Systems without batteries were not selected since the redundancy offered by the batteries is considered essential.

The remaining systems in order by weight are:

6. Pratt and Whitney open cycle fuel cell (1,811 lbs);

7. Batteries (2,132 lbs);

8. Intermittent turbine (2,145 lbs);

9. Hydrogen-oxygen reciprocator (2,154 lbs);

10. Hydrogen-oxygen Brayton cycle turbine (2,186 lbs);

11. Monopropellant turbine (2,294 lbs);

12. Isotope-Brayton cycle turbine (2,305 lbs);

13. Hydrogen-oxygen Stirling cycle reciprocator (2,518 lbs).

As previously stated, the factors of reliability, development status, cost, growth potential, weight, and volume all influence final power system selection. Although minimum weight is important, it alone is not a sufficient basis for selection. It is interesting to note that the weight difference between the P and W closed cycle fuel cell and an all battery system is 736 pounds. This indicates that an all battery system is definitely a contender for this mission if the weight penalty can be tolerated for the gain in reliability. Development status would favor fuel cells over dynamic systems. While fuel cells are not considered to be "fully" developed at the present time, they will be developed under present programs and will be available. Smaller development programs are underway on most of the remaining systems. Growth potential would be likely to favor dynamic systems.

CONCLUSIONS

The P and W fuel cell, both open and closed cycle, is being developed for Apollo and LEM. The remaining development problems associated with this fuel cell are in the category of engineering. Thus the closed cycle P and W cell is the prime recommendation for the Logistics Spacecraft. The Allis-Chalmers hydrogen-oxygen fuel cell has better operational characteristics than the P and W and may be preferred if it is sufficiently developed. The GE cell may be adequate for this mission but it must also be proven on Gemini for which it is being developed. The dynamic systems are in early development stages and could not be recommended with full confidence at this time. Their performance to date has been fair and should improve with continued development. A battery system may be selected if the weight penalty can be tolerated.

REFERENCES

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2. Parker, R. N. and Maxwell, P. T.: The Apollo Auxiliary Power Supply System, NASA Project Apollo Working Paper no. 1041, January 12, 1962.

TABLE I.- POWER SYSTEM CONFIGURATIONS

Conversion system type	Primary conversion system location: Adapter module	Primary conversion system location: Crew module	Energy (kw-hr), Adapter module: Super-critical H_2 and O_2	Adapter module: Subcritical H_2 and O_2	Adapter module: High pressure H_2 and O_2	Adapter module: Battery	Adapter module: Hydrazine (N_2H_4)	Adapter module: Aerozine-50 (50% UDMH/50% N_2H_4) and Nitrogen tetroxide (N_2O_4)	Crew module: Isotope	Crew module: Battery	Crew module: High pressure H_2 and O_2	Crew module: Hydrazine (N_2H_4)	Crew module: Aerozine-50 (50% UDMH/50% N_2H_4) and Nitrogen tetroxide (N_2O_4)	Total system weight (lbs): A-C	Total system weight (lbs): G. E.	Total system weight (lbs): P and W o/c	Total system weight (lbs): P and W c/c
1. Primary batteries	X	X				114.4				35.6				2132			
2. H_2-O_2 fuel cells																	
a.	X		51.5		43.9	19.0				35.6				1653	1870	1870	1583
b.	X			51.5	43.9	19.0				35.6				1639	1857	1847	1571
c.	X		51.5			.9				35.6				2010	2228	1917	1974
d.	X			51.5		62.9				35.6				1995	2215	1894	1962
e.	X				95.4	19.0				35.6				1779	2002	2257	1694
f.	X				51.5	62.9				35.6				2135	2361	2357	2086
g.		X	51.5		43.9	19.0				15.3	20.3			1559	1806	1834	1408
h.		X		51.5	43.9	19.0				15.3	20.3			1530	1793	1811	1396
i.		X			95.4	19.0				15.3	20.3			1685	1926	2221	1518
j.		X	51.5			62.9				15.3	20.3			1915	2164	1881	1799
k.		X		51.5		62.9				15.3	20.3			1901	2151	1858	1787
l.		X			51.5	62.9				15.3	20.3			2041	2302	2321	1911
3. Storable fuel cell				(oxygen only)	(oxygen only)						(oxygen only)						
a.	X			51.5*		62.9	51.5*			35.6				2012			
b.	X			51.5*	43.9*	19.0	95.4*			35.6				1672			
c.		X		51.5*	43.9*	19.0	95.4*			15.3	20.3*	20.3*		1554			
d.		X			43.9*	70.5	43.9*			15.3	20.3*	20.3*		2055			
4. Monopropellant turbine																	
a.	X					19.0	95.4			35.6				2294			
b.	X					62.9	51.5			35.6				2492			
c.		X				19.0	95.4			15.3		20.3		2361			
d.		X				70.5	43.9			15.3		20.3		2508			
e.		X					114.4					35.6		2368			
5. Pulse turbine																	
a.	X					19.0		95.4		35.6				2153			
b.	X					62.9		51.5		35.6				2366			
c.		X				19.0		95.4		15.3			20.3	2145			
d.		X				70.5		43.9		15.3			20.3	2395			
e.		X						114.4					35.6	1816			

*Oxidizer and fuel are supplied in the proper ratios so that the combination provides the required total energy.

TABLE I. - POWER SYSTEM CONFIGURATIONS - Continued

Conversion system type	Primary conversion system location: Adapter module	Primary conversion system location: Crew module	Energy (kw-hr), Adapter module: Super-critical H_2 and O_2	Adapter module: Subcritical H_2 and O_2	Adapter module: High pressure H_2 and O_2	Adapter module: Battery	Adapter module: Hydrazine (N_2H_4)	Adapter module: Aerozine-50 (50% UDMH/50% N_2H_4) and Nitrogen tetroxide (N_2O_4)	Crew module: Isotope	Crew module: Battery	Crew module: High pressure H_2 and O_2	Crew module: Hydrazine (N_2H_4)	Crew module: Aerozine-50 (50% UDMH/50% N_2H_4) and Nitrogen tetroxide (N_2O_4)	Total system weight (lbs)
6. Hypergolic reciprocator														
a.	X					19.0		95.4		35.6				1819
b.	X					62.9		51.5		35.6				2164
c.		X				19.0		95.4		15.3			20.3	1793
d.		X				70.5		43.9		15.3			20.3	2134
e.		X						114.4					35.6	1642
7. H_2-O_2 reciprocator														
a.	X		51.5		43.9	19.0				35.6				2260
b.	X			51.5	43.9	19.0				35.6				2226
c.	X		51.5			62.9				35.6				2188
d.	X			51.5		62.9				35.6				2154
e.	X				95.4	19.0				35.6				2778
f.	X				51.5	62.9				35.6				2706
g.		X	51.5		43.9	19.0				15.3	20.3			2416
h.		X		51.5	43.9	19.0				15.3	20.3			2382
i.		X			95.4	19.0				15.3	20.3			2934
j.		X	51.5			62.9				15.3	20.3			2344
k.		X		51.5		62.9				15.3	20.3			2310
l.		X			51.5	62.9				15.3	20.3			2862
8. H_2-O_2 Stirling cycle reciprocator														
a.	X		51.5		43.9	19.0				35.6				2630
b.	X			51.5	43.9	19.0				35.6				2586
c.	X		51.5			62.9				35.6				2562
d.	X			51.5		62.9				35.6				2518
e.	X				95.4	19.0				35.6				3084
f.	X				51.5	62.9				35.6				3016
g.		X	51.5		43.9	19.0				15.3	20.3			2831
h.		X		51.5	43.9	19.0				15.3	20.3			2787
i.		X			95.4	19.0				15.3	20.3			3285
j.		X	51.5			62.9				15.3	20.3			2763
k.		X		51.5		62.9				15.3	20.3			2719
l.		X			51.5	62.9				15.3	20.3			3217

TABLE I.- POWER SYSTEM CONFIGURATIONS - Concluded

Conversion system type	Primary conversion system location		Energy (kw-hr)											Total system weight (lbs)
			Adapter module						Crew module					
	Adapter module	Crew module	Super-critical H_2 and O_2	Subcritical H_2 and O_2	High pressure H_2 and O_2	Battery	Hydrazine (N_2H_4)	Aerozine-50 (50% UDMH/50% N_2H_4) and Nitrogen tetroxide (N_2O_4)	Isotope	Battery	High pressure H_2 and O_2	Hydrazine (N_2H_4)	Aerozine-50 (50% UDMH/50% N_2H_4) and Nitrogen tetroxide (N_2O_4)	
9. H_2-O_2 Brayton cycle turbine														
a.	X		51.5		43.9	19.0				35.6				2218
b.	X			51.5	43.9	19.0				35.6				2186
c.	X		51.5			62.9				35.6				2311
d.	X			51.5		62.9				35.6				2279
e.	X				95.4	19.0				35.6				2546
f.	X				51.5	62.9				35.6				2642
g.		X	51.5		43.9	19.0				15.3	20.3			2354
h.		X		51.5	43.9	19.0				15.3	20.3			2322
i.		X			95.4	19.0				15.3	20.3			2682
j.		X	51.5			62.9				15.3	20.3			2447
k.		X		51.5		62.9				15.3	20.3			2415
l.		X			51.5	62.9				15.3	20.3			2778
m.		X	114.4								35.6			1854
n.		X		114.4							35.6			1778
10. Isotope-Stirling cycle reciprocator		X				19.0			(Po-210) 115.7	15.3				2560
11. Isotope-Brayton cycle turbine		X				19.0			(Po-210) 115.7	15.3				2305
12. Isotope-Rankine cycle turbine		X				19.0			(Po-210) 115.7	15.3				2937

TABLE II.- POWER CONDITIONING WEIGHTS

Assumptions: (1) The desired electrical output is 40 percent of total power as 400 cps a-c and 60 percent as d-c.

(2) A 20-lb wire weight was used throughout.

(3) No redundancy is included in the calculations.

1. Primary batteries: Output is all d-c

d-c: 60 percent × 4.6 kw = 2.76 kw
a-c: 40 percent × 4.6 kw = 1.84 kw
(Used throughout Table II)

d-c:	Regulator 7.5 lb/kw × 2.76 kw =	20.7 lb
a-c:	Regulator 7.5 lb/kw × 1.84 kw =	13.8 lb
	Inverter 32 lb/kw × 1.8 kw =	58.8 lb
Wire		20.0 lb
	TOTAL	113.3 lb

2 and 3. Fuel cells: Same as no. 1

4. Storable monopropellant turbine: Alternator output is 400 cps a-c.

d-c transformer-rectifier	15 lb/kw × 2.76 kw =	41.4 lb
a-c and d-c regulators (refer to no. 1):	20.7 + 13.8 =	34.5 lb
Wire		20.0 lb
	TOTAL	95.9 lb

5. Storable bipropellant (intermittent) turbine: Alternator output is 3,000 cps a-c (frequency regulator for intermittent operation is assumed to be a part of the engine fixed weight)

d-c:	transformer-rectifier	15 lb/kw × 2.76 kw =	41.4 lb
a-c:	frequency changer	20 lb/kw × 1.84 kw =	36.8 lb
a-c and d-c:	regulator	=	34.5 lb
Wire			20.0 lb
		TOTAL	132.7 lb

6. Storable bipropellant (hypergolic) reciprocator: Generator output is d-c.

Same as no. 1

TABLE II.- POWER CONDITIONING WEIGHTS - Concluded

7. H_2-O_2 reciprocator: Alternator output is 400 cps a-c

   Same as no. 4.

8. H_2-O_2 Stirling cycle reciprocator: Alternator output is 400 cps a-c.

   Same as no. 4.

9. H_2-O_2 Brayton cycle turbine: Alternator output is 400 cps a-c.

   Same as no. 5.

10. Isotope - Stirling cycle reciprocator.

    Same as no. 4.

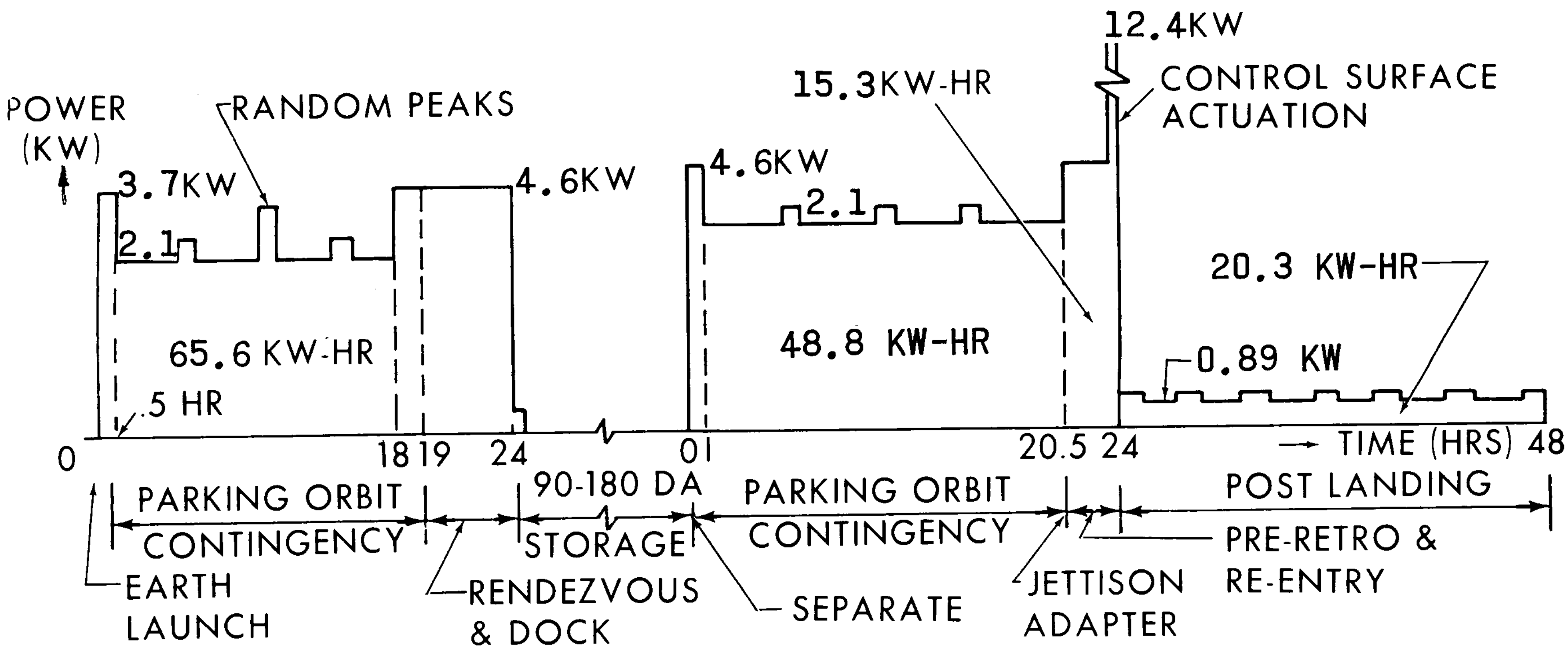
11. Isotope - Brayton cycle turbine.

    Same as no. 5

12. Isotope - Rankine cycle turbine: Alternator output is 2,000 cps. Weight is approximately the same as no. 5.

POWER PROFILE

FOR MAXIMUM ENERGY REQUIREMENTS



(TOTAL ENERGY 150 KW-HR)

FIGURE 1

POWER PROFILE FOR MINIMUM ENERGY REQUIREMENTS

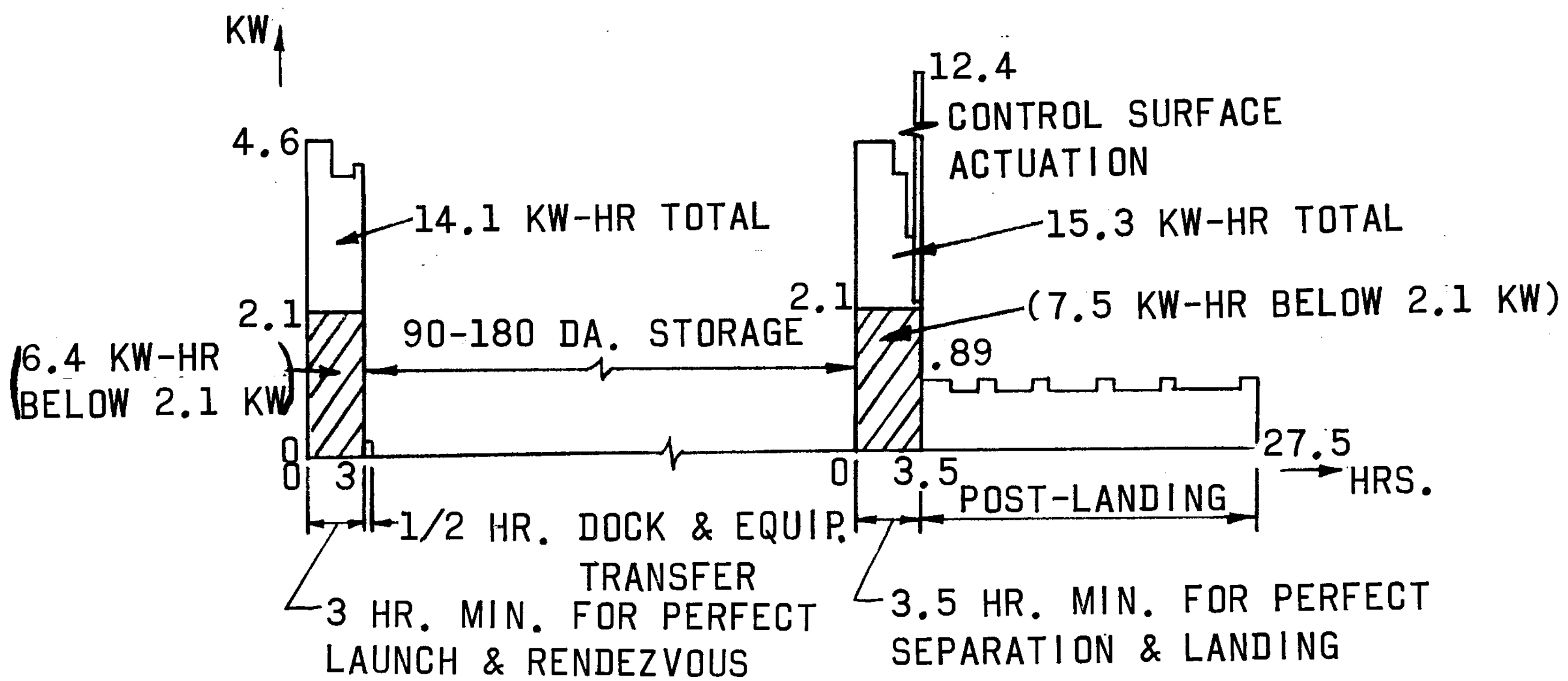


FIGURE 2

ENERGY BLOCKS CORRESPONDING
TO FIGURE 1

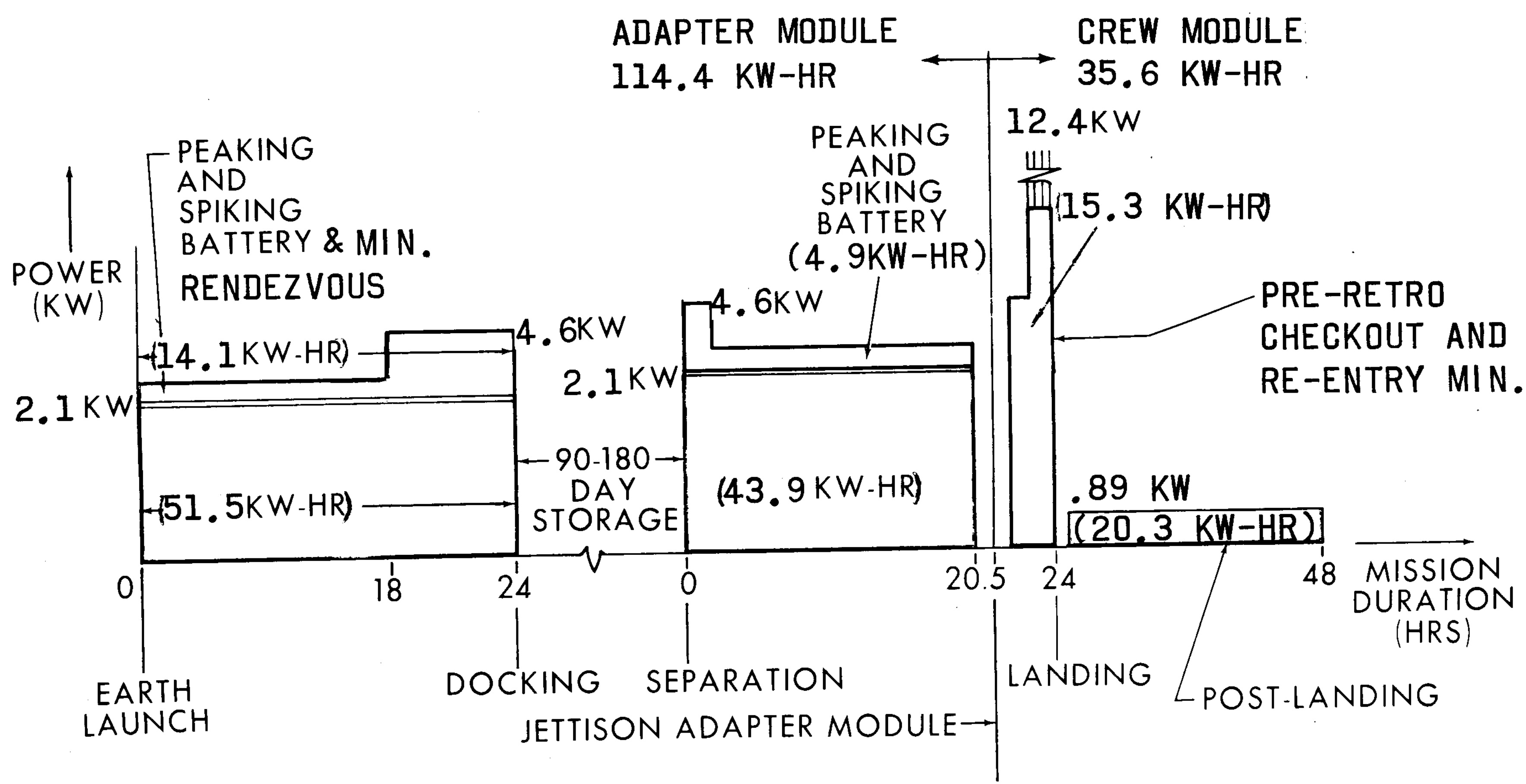


FIGURE 3

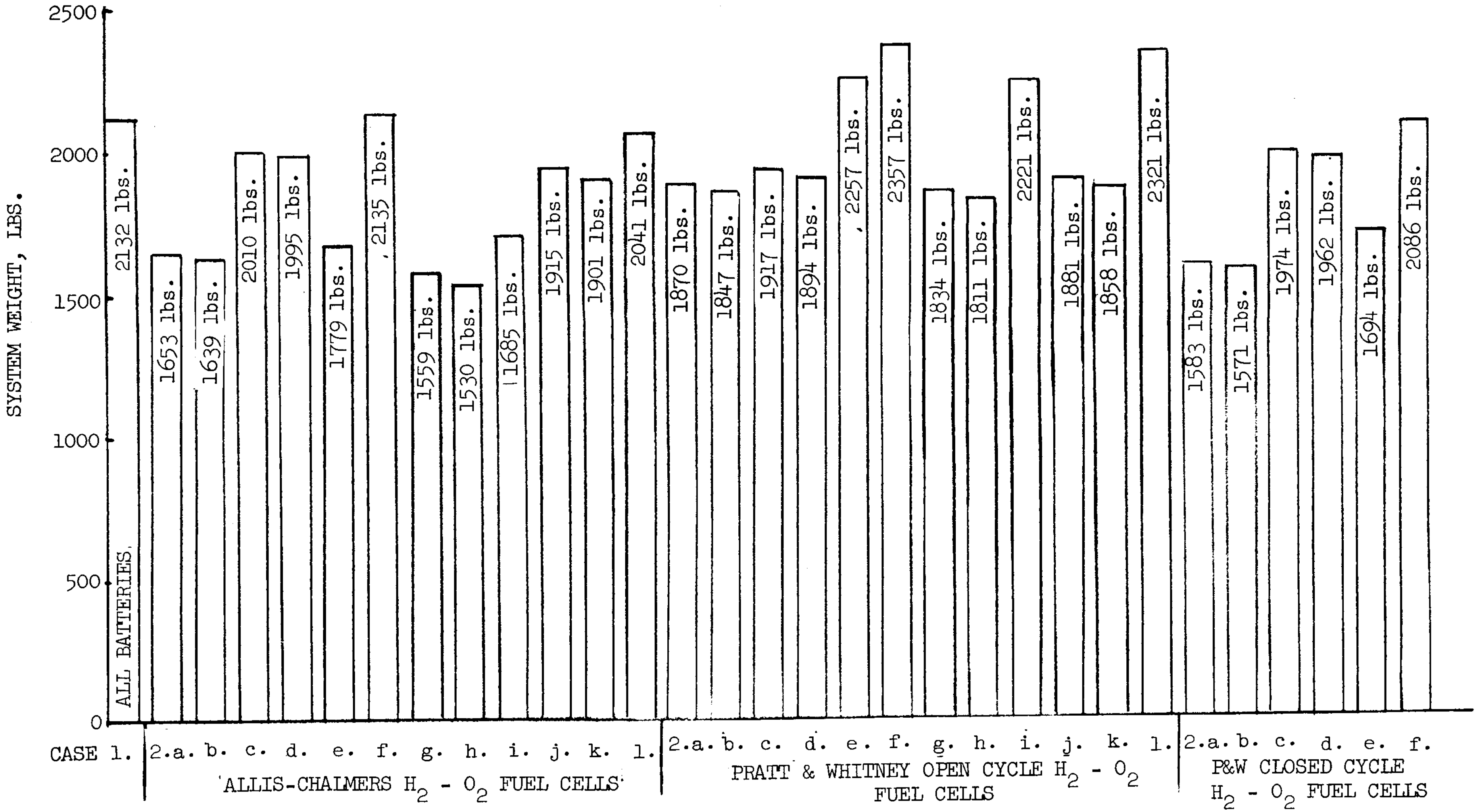


Figure 4.- System weights.

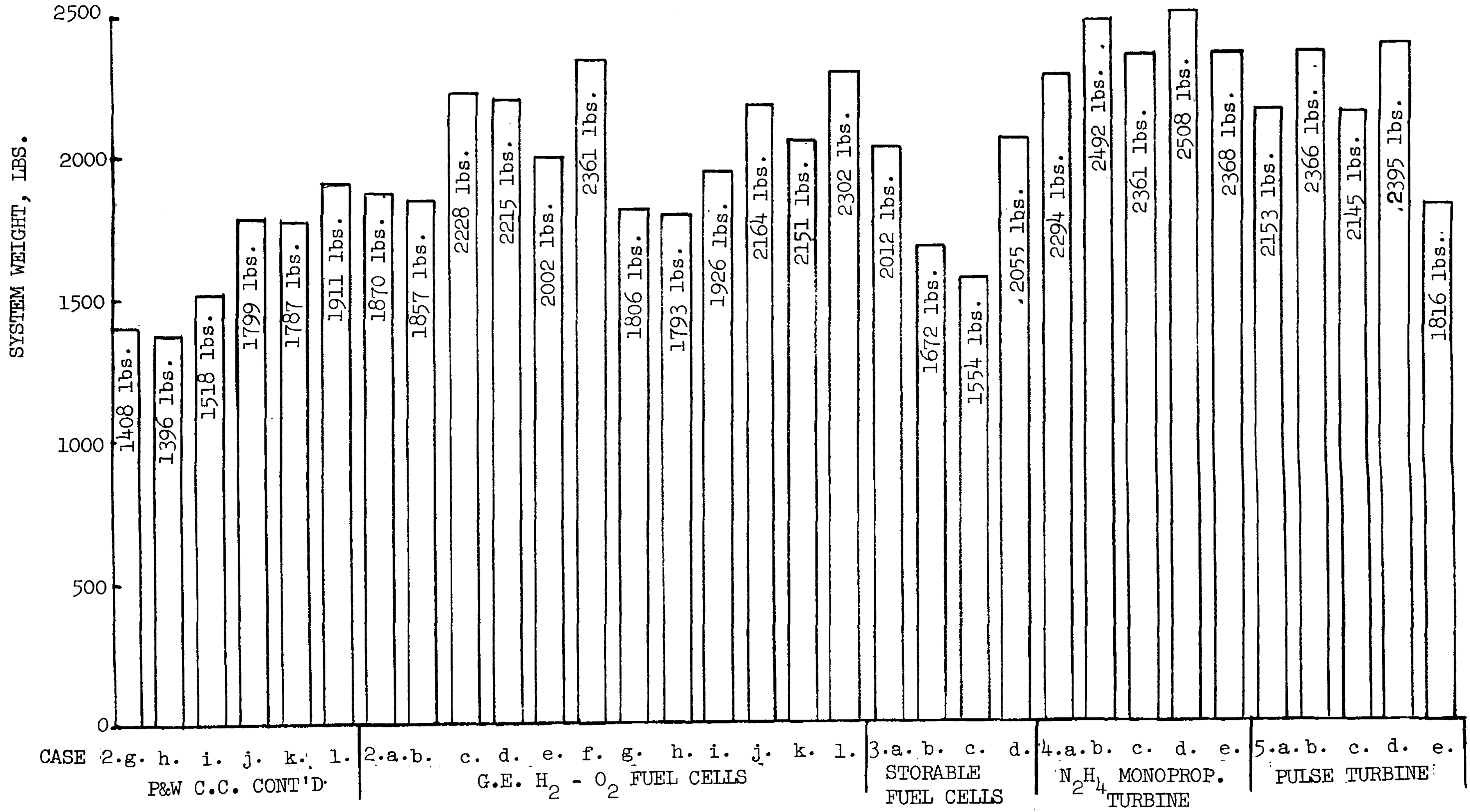


Figure 4.- Continued.

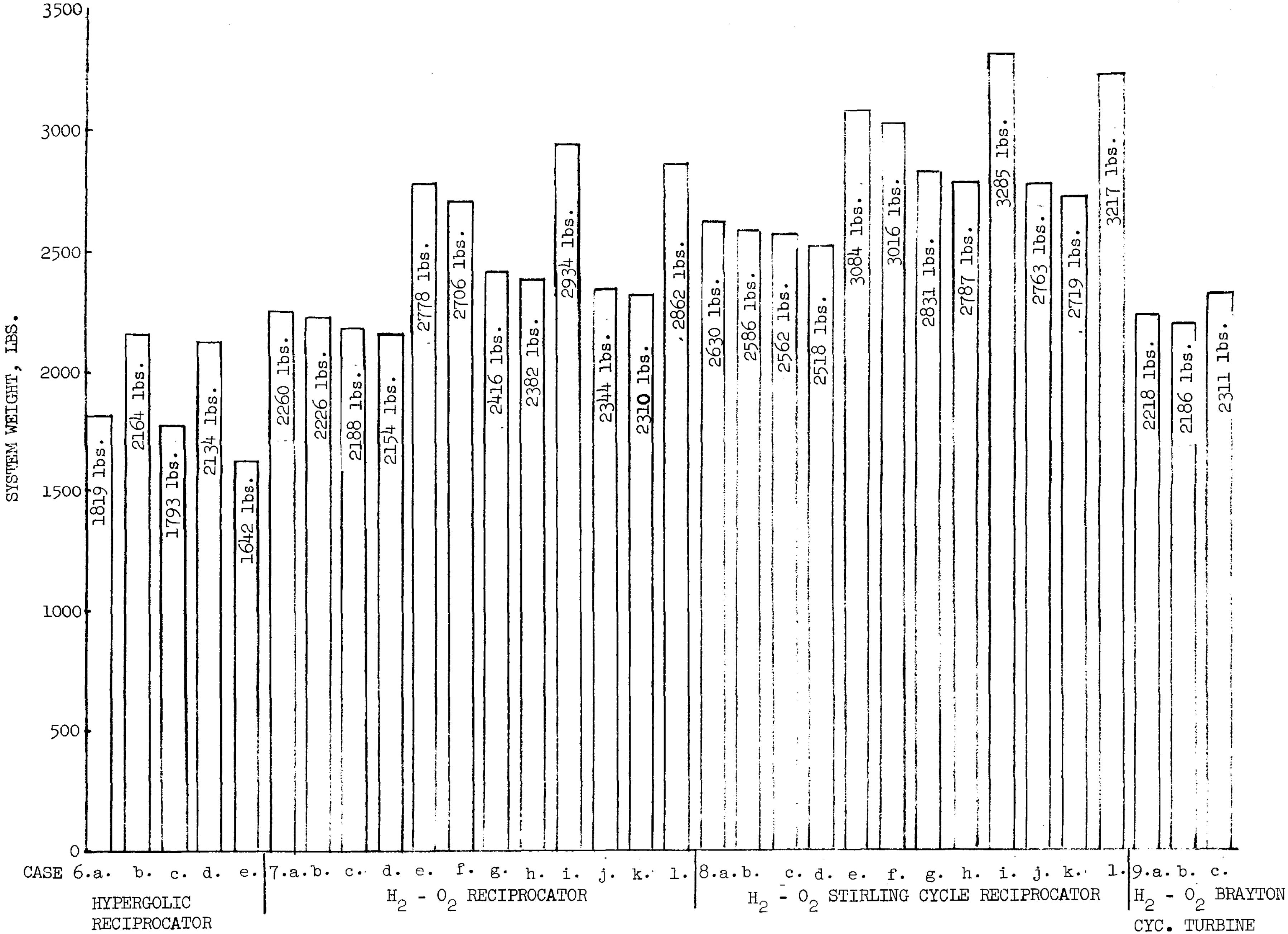


Figure 4.- Continued.

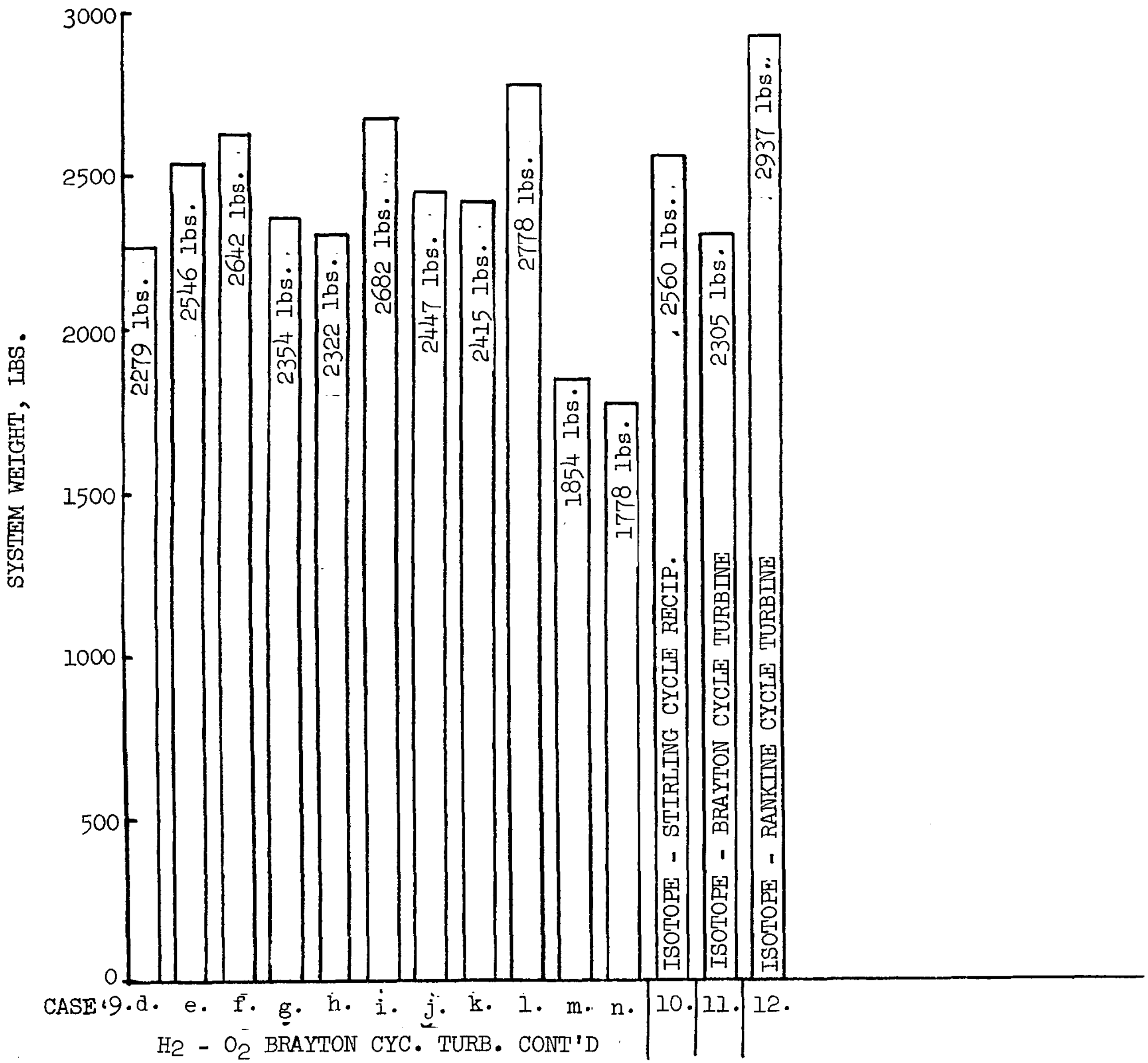


Figure 4.- Concluded.

APPENDIX A

ANALYSIS OF THERMAL CONTROL SYSTEMS

By: J. A. Bonner
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APPENDIX A

ANALYSIS OF THERMAL CONTROL SYSTEMS

SUMMARY

This analysis is directed toward establishing an effective thermal control system for rejecting the heat resulting from the inefficiencies of the electrical power system for the Logistics Spacecraft of the Manned Orbiting Space Station.

Heat rejection by space radiators and water evaporation is considered. A combination of the two systems is also treated. Each of the thermal control systems is considered for five possible electrical power systems.

These considerations favor the selection of space radiators for the heat rejection system. Additional work is necessary to more firmly establish this selection due to the difficulty in establishing radiator weights.

INTRODUCTION

The basic objective of the Logistics Spacecraft is to transport twelve personnel and maximum cargo to and from the Manned Orbiting Space Station (MOSS).

As shown in figure A-1, a maximum active flight time of 48 hours has been stipulated, including 24 hours from launch to docking and 24 hours for recall. A habitable environment must be provided for the crew for one day following landing. The spacecraft and its subsystems will be capable of unpressurized orbital storage for six months.

This analysis is concerned with five of the power systems being considered for supplying the Logistics Spacecraft electrical power. These electrical power systems are: (1) H_2-O_2 fuel cell, (2) storable propellant fuel cell, (3) H_2-O_2 reciprocator, (4) hypergolic reciprocator, and (5) Stirling cycle reciprocator.

The objective of this analysis is to investigate methods for rejecting heat resulting from the inefficiencies of the electrical power system for the spacecraft. Two methods of thermal control are treated; heat rejection by space radiators and by water evaporation. A combination of the two systems is also considered. No specific configuration was assumed for the Logistics Spacecraft, but instead flat plate orientations were assumed for the radiator surfaces.

LIST OF SYMBOLS

A_R	Radiator area, ft^2
Q	Net heat rejection, Btu/hr-ft^2
α	Surface solar absorptivity
ϵ	Surface emissivity
γ	Angle between normal to flat plate and position vector. The position vector is a line from the center of the earth to the vehicle, degrees.
ϕ_c	Angle between plane formed by sun vector and position vector, and plane formed by normal vector and position vector, degrees.
ϕ_s	Angular position in orbit from earth-sun line or subsolar point, degrees.

RADIATOR SYSTEM ANALYSIS

The rejection of heat by space radiators depends greatly upon their orientation with respect to the sun and nearby planetary bodies. In this analysis several radiator orientations have been assumed in order to show the effect of orientation on radiator area. The orientations chosen will give maximum and minimum values of radiator area.

The design point for the radiators was chosen as the point during an orbit where there is minimum net heat exchange between the radiator and its environment. The design point coincides with the point of maximum environmental sink temperature.

The following assumptions apply:

a. Solar constant = 445 Btu/hr-ft^2

b. Earth reflected solar radiation = 169 $Btu/hr\text{-}ft^2$

c. Earth thermal radiation = 68 $Btu/hr\text{-}ft^2$

d. 300 nautical mile circular orbit

e. All surfaces radiate diffusely

f. Uniform temperature radiator

g. Space radiator characteristics:

   1. Surface solar absorptivity = 0.18

   2. Surface thermal emissivity = 0.90

   3. 100 percent fine efficiency

h. Radiators are inactive during launch and reentry; water evaporation will be used during this period.

Figure A-2 shows pertinent angles for radiator orientation, and figure A-3 shows the radiator orientations used in this analysis. Figure A-4 shows typical net radiator heat rejection profiles for each of the orientations chosen. From the typical heat rejection profile for each case, the point of maximum environmental sink temperature can be found. Figure A-5 shows a plot of radiator area per unit of heat rejection for a range of radiator temperatures based on the maximum environmental sink temperature of each case. The maximum sink temperature is tabulated on figure A-5 for each case.

By the use of table A-I, which gives the electrical power system inefficiencies and radiator temperature, and figure A-5, the maximum areas can be calculated. The maximum areas are shown in figure A-6 for each case and each electrical power system.

The design point considered allows the radiator to reject the maximum heat load at its point of minimum heat rejection. There must be some method of controlling radiator performance as the radiator moves away from this minimum heat rejection point, and also for lower heat loads. Control of heat rejection is necessary for optimum system performance and prevention of radiator fluid freezing when exposed to a low temperature environment. The transport fluid must also be chosen so that it is compatible with the maximum expected temperature realized from the electrical power system. In this analysis, no attempt was made to select a transport fluid.

Radiator weights are based on 0.55 pounds per square foot of radiator area for fin and tube type radiators. This value seems to be current with the state-of-the-art in radiator design. The above 0.55 lbs/ft^2 includes only the weight of the radiator and does not include meteoroid shielding, pumps, valves or transport fluid weights. As was stated in the assumptions, the radiator was considered inactive during launch and reentry. These phases of the mission would require a water evaporation system weighing approximately ten pounds. This water weight was included in the radiator system weights. Figure A-7 shows maximum radiator weights based on the previous assumptions. The weights are based on the maximum peak power system inefficiencies as shown in table A-I.

WATER EVAPORATIVE SYSTEM ANALYSIS

The rejection of heat by a water evaporative system depends upon the thermo-physical properties of water and the rate at which water is vented to the space environment. The space environment does not affect the heat rejection rate of a water evaporative system.

The following assumptions apply:

a. Maximum heat of vaporization of water = 1071.7 Btu/lb (at 14.7 psia).

b. Heat is transferred to the water by means of a closed cooling loop and water boiler.

c. 10-percent weight penalty for H_2O tankage.

The weight of the water evaporative system depends only on the heat of vaporization of H_2O and the total amount of heat to be rejected. The weight of the components for the cooling loop is not included. Figure A-7 shows the required water evaporative system weights. These weights are based on the total electrical power system inefficiencies from table A-I.

COMBINATION SYSTEM ANALYSIS

A combination system consisting of a space radiator and a water boiler is considered. The same general assumptions apply for the combination system components as for the individual systems.

It is assumed that the radiator operates continuously and that the water evaporative system handles any heat the radiator cannot reject. It was also assumed that for a given radiator the effective radiator area would be varied to handle lower heat loads.

The analysis consists of selecting radiator areas and determining how must of the required load each could reject. The remaining heat is rejected by the water evaporative system. Areas are chosen up to and including the maximum possible area for each electrical power system.

A radiator area of zero indicates that an all water evaporation system is used. Any radiator between the maximum area for each conversion system and the minimum area of zero requires that it be combined with a water evaporator for orbital cooling.

Radiator areas are based on a radiator orientation of $\gamma = 90°$ and $\phi_L = 0$ since the largest area results from this orientation.

Figure A-8 shows a plot of the combination system weight for radiator areas from zero to the maximum for each electrical power system, and also a plot of radiator weight. The water weight required is thus the difference between the combination system weight and the radiator weight. Each curve ends with the area required for a pure radiator system. If water boil-off is not assumed to be used during launch and reentry, the combination system curve would intersect that of radiator weight at the maximum required radiator area.

Figure A-9 shows a plot of the combination system weight for the hypergolic reciprocator and H_2-O_2 fuel cell for radiator weights of 0.55 lbs/ft^2 and 1.10 lbs/ft^2. It is seen that as the radiator weight increases that the difference between the maximum radiator weight and the optimum combination system weight increases.

The optimum combination system weight, obtained from figure A-8, for each electrical power system is shown on figure A-7, along with those for the radiator system and water evaporative system.

SYSTEM COMPARISON

From figure A-6, it is seen that case II gives the largest radiator area for all electrical power systems. This is also the maximum radiator area for all orientations. If this area is used, the radiator can handle the peak load in any orientation and hence the vehicle would be free to maneuver in all directions. It is noticed that there are other orientations which result in lower weights, but they require a restriction to be put on the radiator orientation and hence on the vehicle.

From figure A-7, we see that the radiator weights are lower than those of the water evaporative system. The radiator system has the disadvantage in its tendency to freeze. Design and control can overcome the freezing problem when the radiators are active; however, when the radiators are stored during the six-month docking period some method to prevent freezing must be used in order to prevent structural damage. The water evaporative system is the simpler of the two systems and can achieve the desired heat rejection, unaffected by the changing space environmental sink temperature; however, its weight is prohibitively high. The radiator system has the advantage of higher mission flexibility, because the system weight is affected very little by time in orbit.

Figure A-8 shows the weights of the combination system. It is seen that the optimum point results in a lower system weight than that of the radiator system, but the weight savings is not very significant. For the combination system to be used, there should be a significant weight savings over both of the individual systems, due to the increased complexity of using two separate systems in combination.

The weight savings of the combination system will become more attractive over the radiator system as the area of the radiator system increases, as shown in figure A-9. Before the combination system can be eliminated, additional weight analysis on the radiator system must be made to include fluid, pump, valve and plumbing weights.

CONCLUDING REMARKS

The major requirements of an efficient thermal control system are simplicity, reliability, minimum weight, and ease of maintenance.

A radiator system is reliable and relatively uncomplicated. The radiator system is lighter than a water evaporative system, as illustrated by the hypergolic reciprocator electrical power system which requires a radiator system of 98.6 pounds and a water evaporative system of 907.8 pounds. However, the water evaporative system is reliable, simple, and easy to maintain.

The combination system for the hypergolic reciprocator weighs 80.0 pounds which is not a significant enough weight saving over the radiator system to make it desirable.

Since weight is a prime selection criteria, the radiator system appears to be the best system based on the assumptions of this preliminary analysis.

TABLE A-I.- POWER SYSTEM INEFFICIENCIES

Power System	Radiator Temperature °R	Thermal Efficiency Percent	Inefficiencies-Percent Input		Heat To Be Rejected	
			Heat Rejected By Venting Exhaust To Space	Heat To Be Rejected	Maximum Peak Btu/Hr	Total Accumulative Btu
H_2-O_2 Fuel Cell	660	55	16	29	8,250	224,400
Storable Propellant Fuel Cell	620	50	0	50	15,560	421,850
H_2-O_2 Reciprocator	840	30	15	55	28,500	773,400
Hypergolic Reciprocator	660	27	17	56	32,250	875,000
Stirling Cycle Reciprocator	760	30	15	55	28,500	773,400

Inefficiencies Based On Power Requirements Of:

(1) Maximum peak = 4,600 Watts

(2) Total accumulative = 126.4 KWH (excludes post landing)

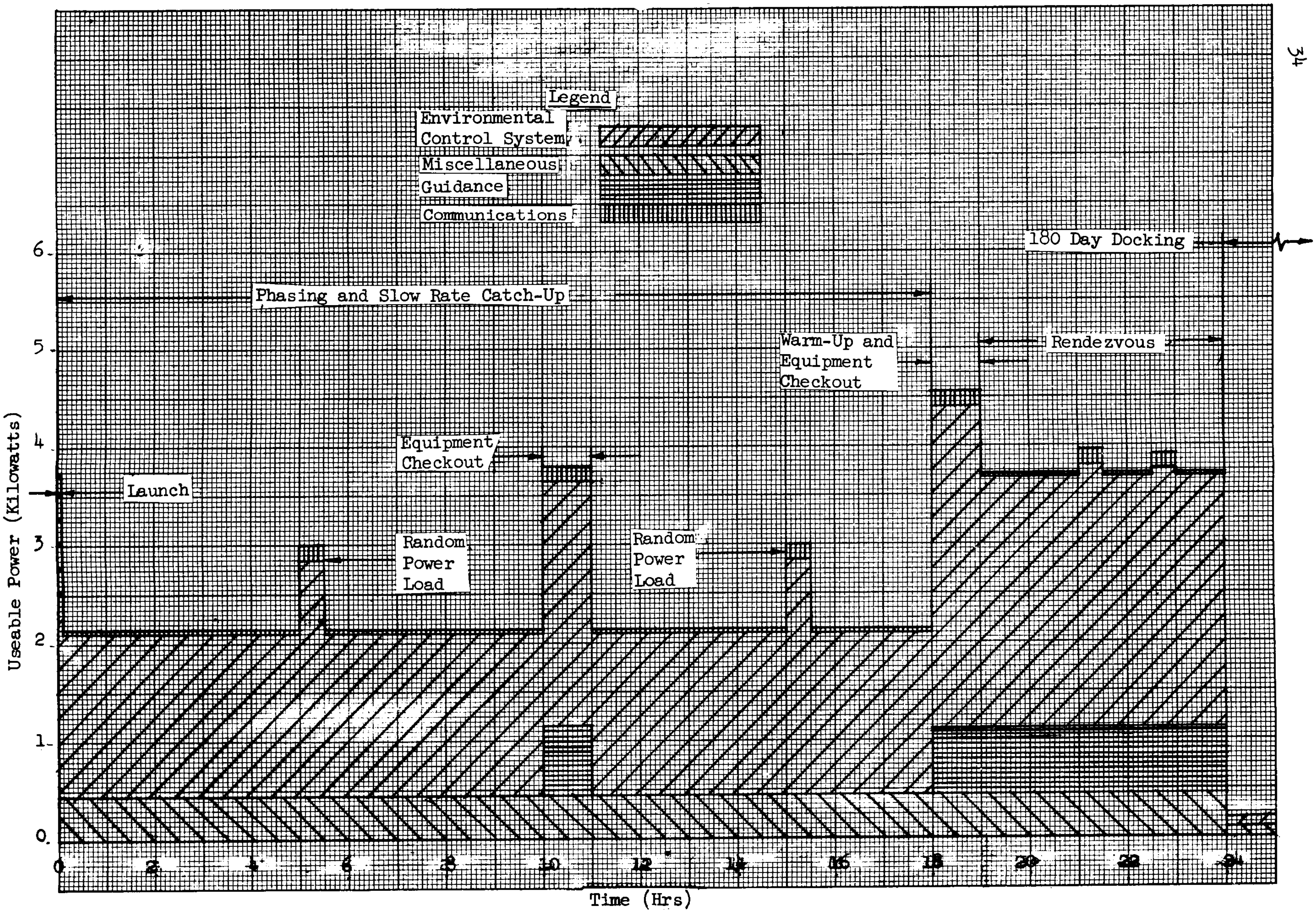


Figure A-1.- Preliminary power profile for the Space Station Logistics Spacecraft 12 man configuration

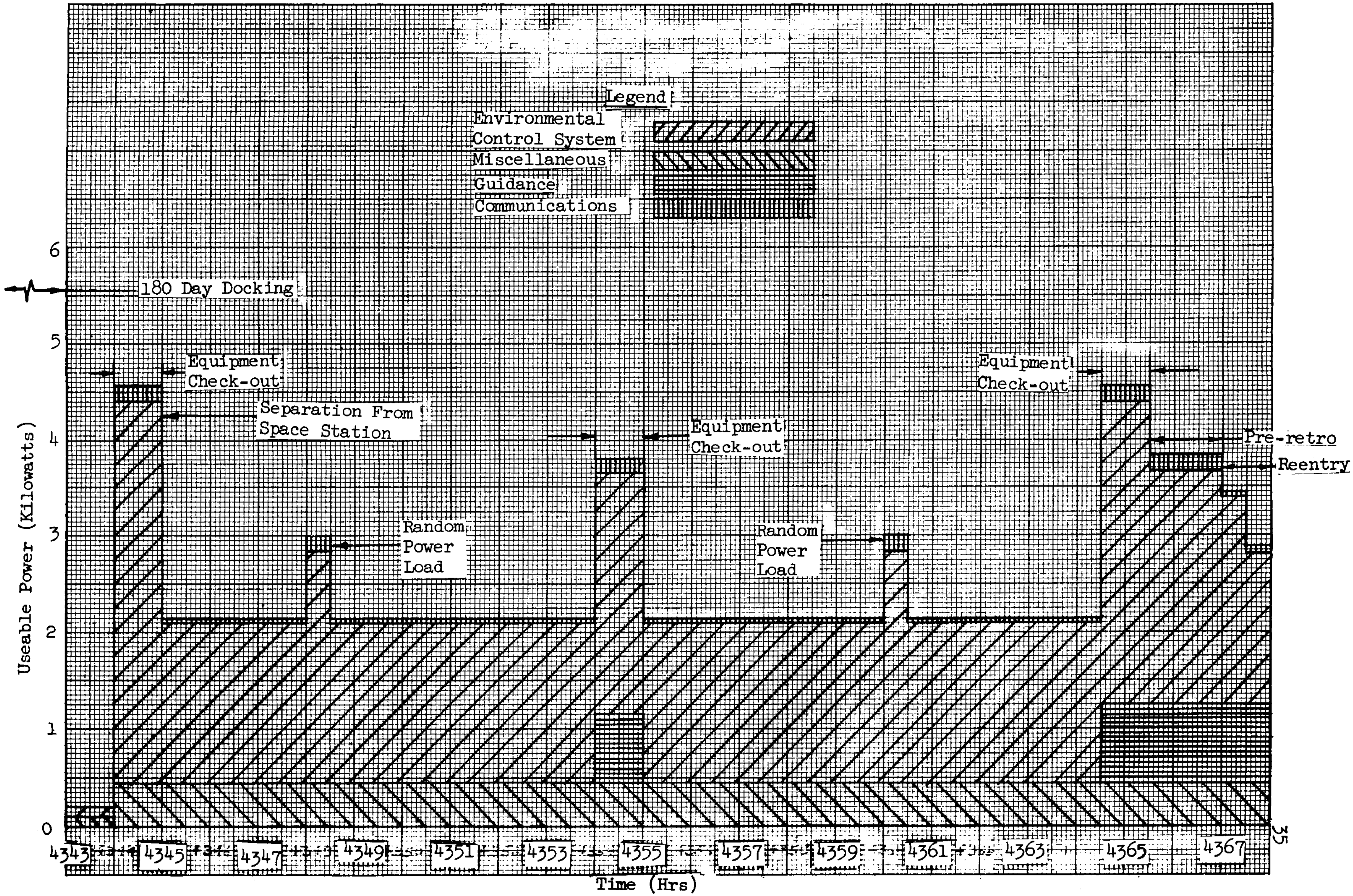
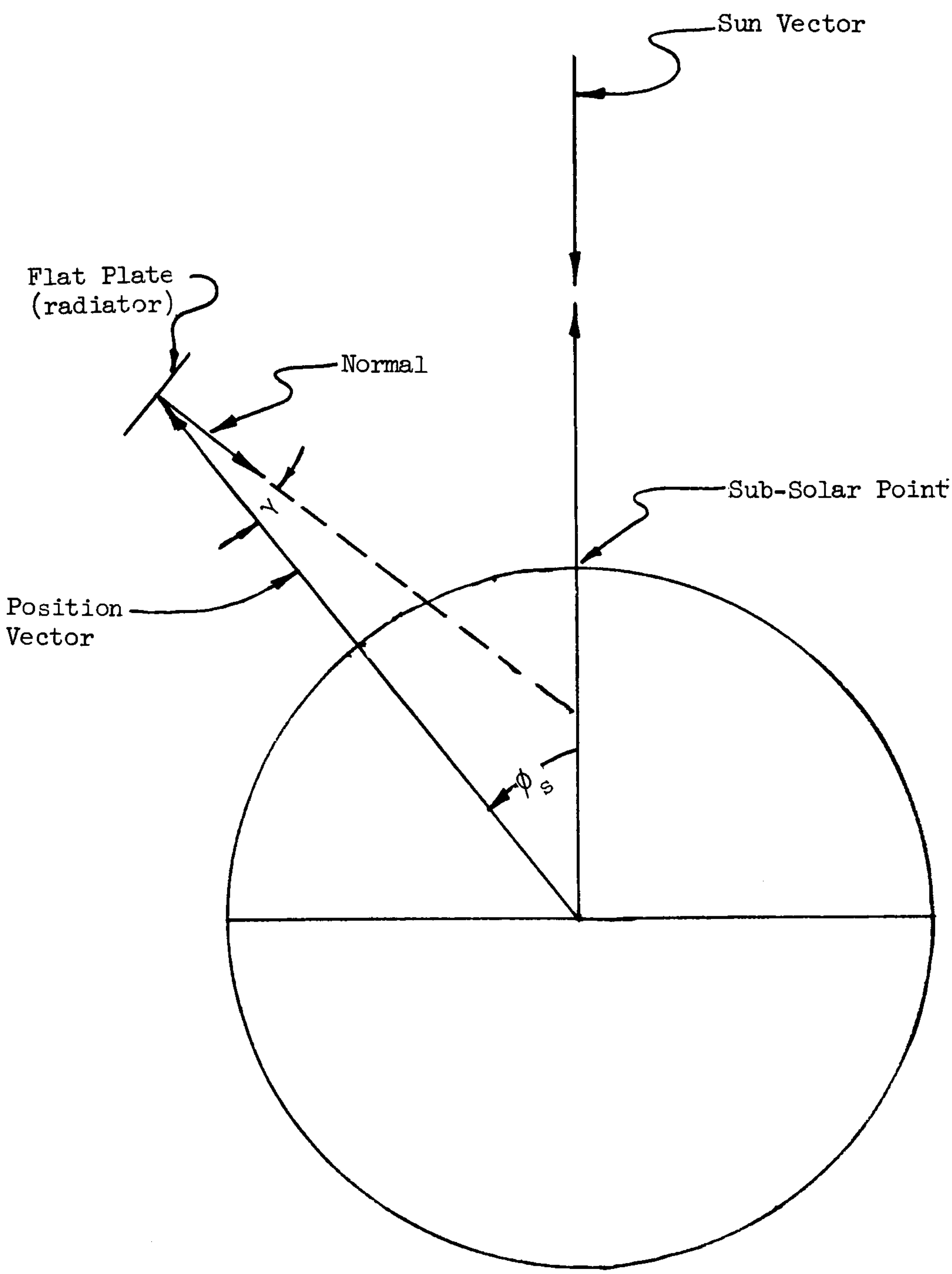
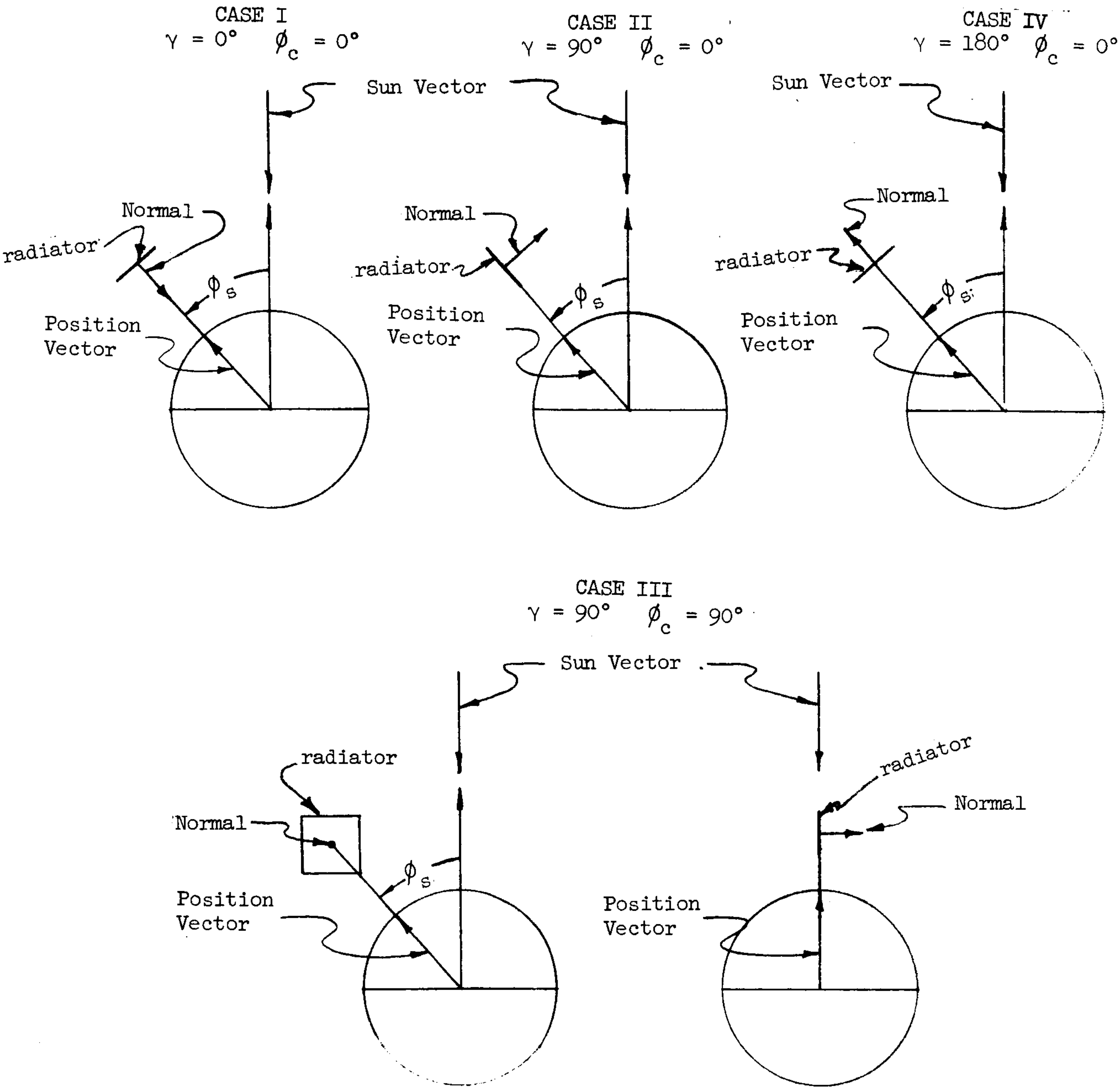


Figure A-1.- Preliminary power profile for the Space Station Logistics Spacecraft 12 man configuration - Concluded



ϕ_c - Angle between plane formed by sun vector and position vector and plane formed by normal vector and position vector.

Figure A-2.- Radiator position vectors



*NOTE:
Orbital plane is formed by position vector and sun vector.

Figure A-3.- Radiator orientations

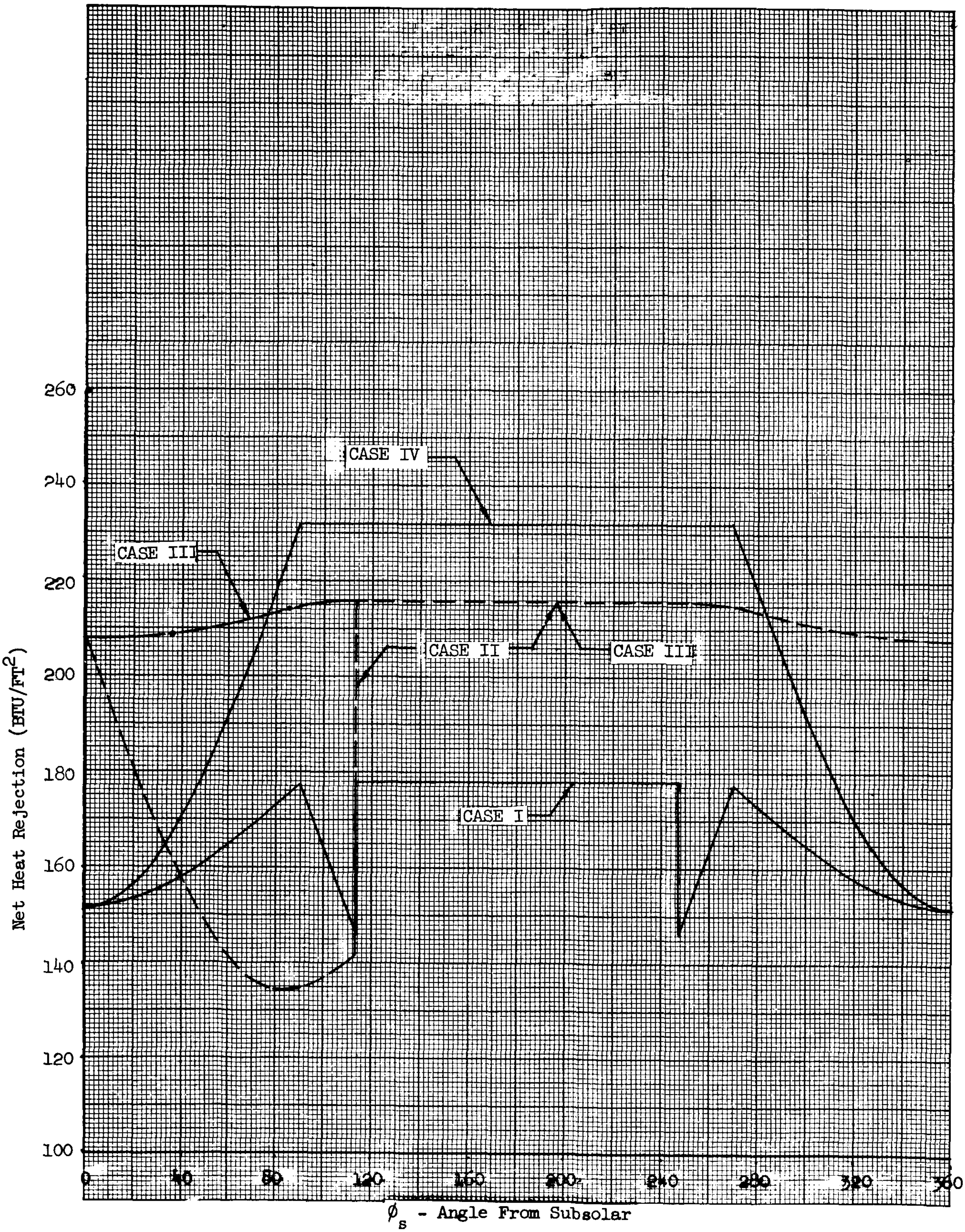


Figure A-4.- Typical radiator heat rejection profile
300 nautical mile orbit

TR = 620° R E = 0.90 α/E = 0.20

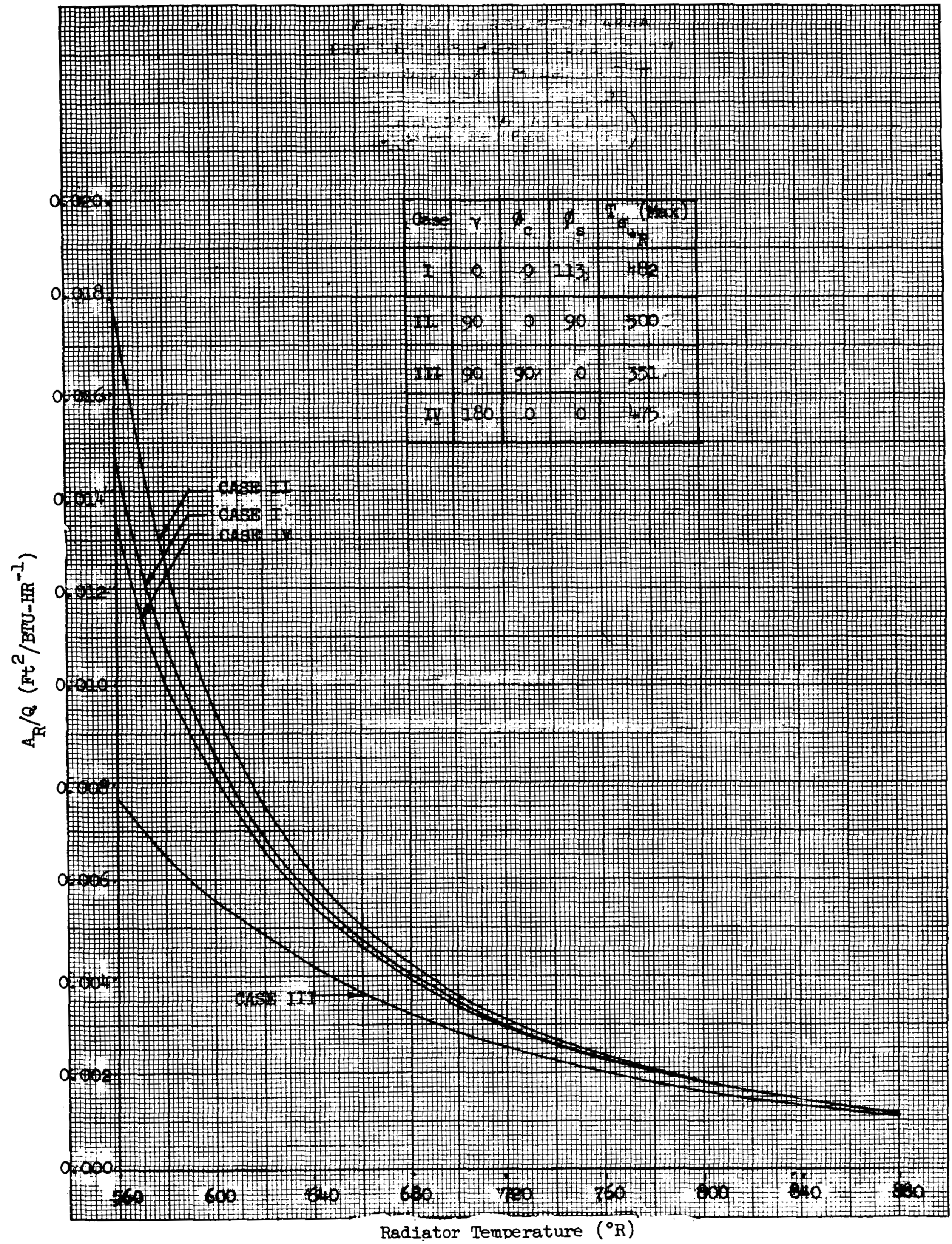


Figure A-5.- Flat plate radiator area per unit of heat rejection
300 nautical mile orbit

$\alpha/E = 0.20 \quad E = 0.90$

(Based on maximum sink temperatures)

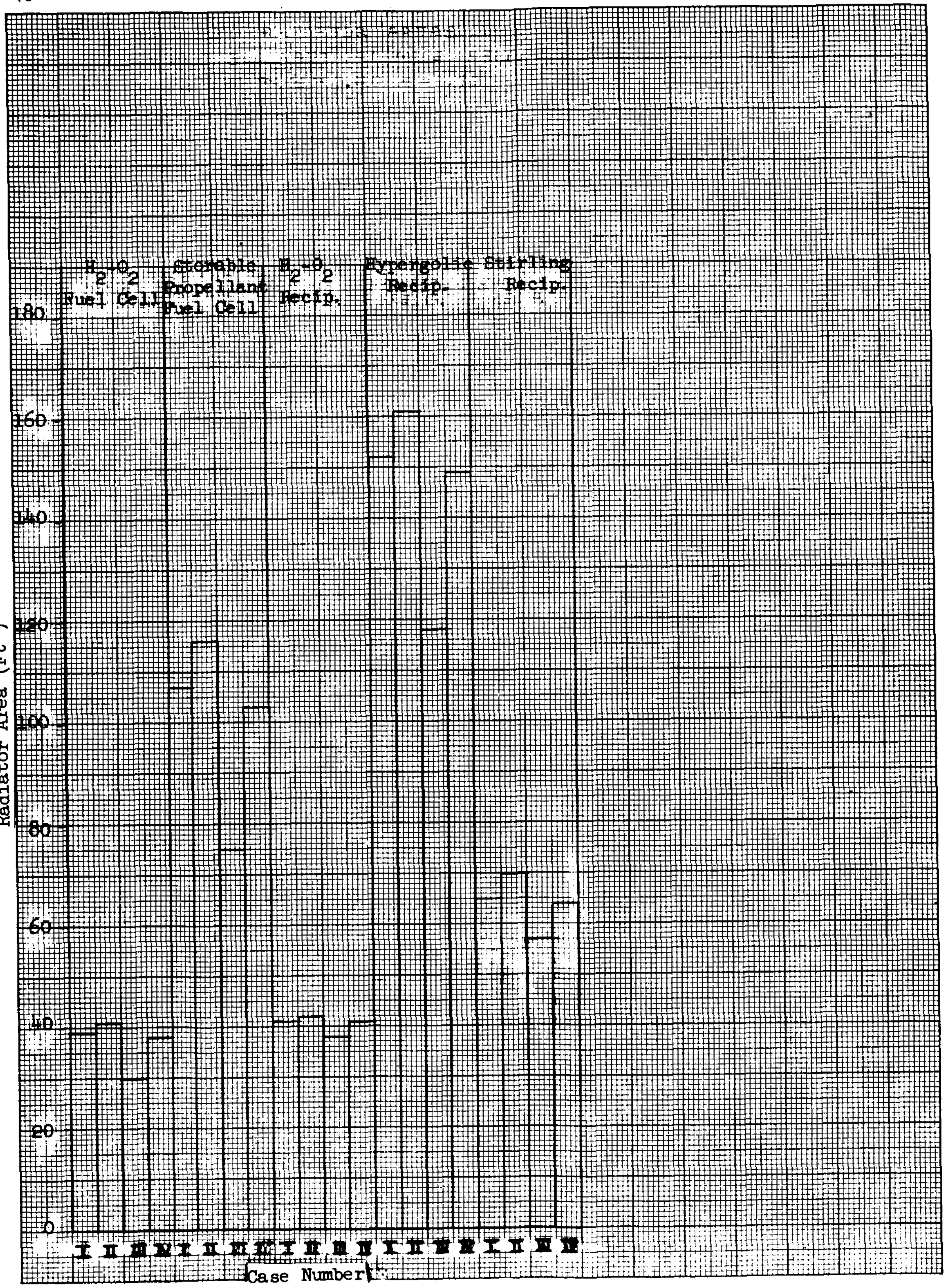


Figure A-6.- Radiator areas
300 nautical mile orbit
$\alpha/E = 0.20 \quad E = 0.90$

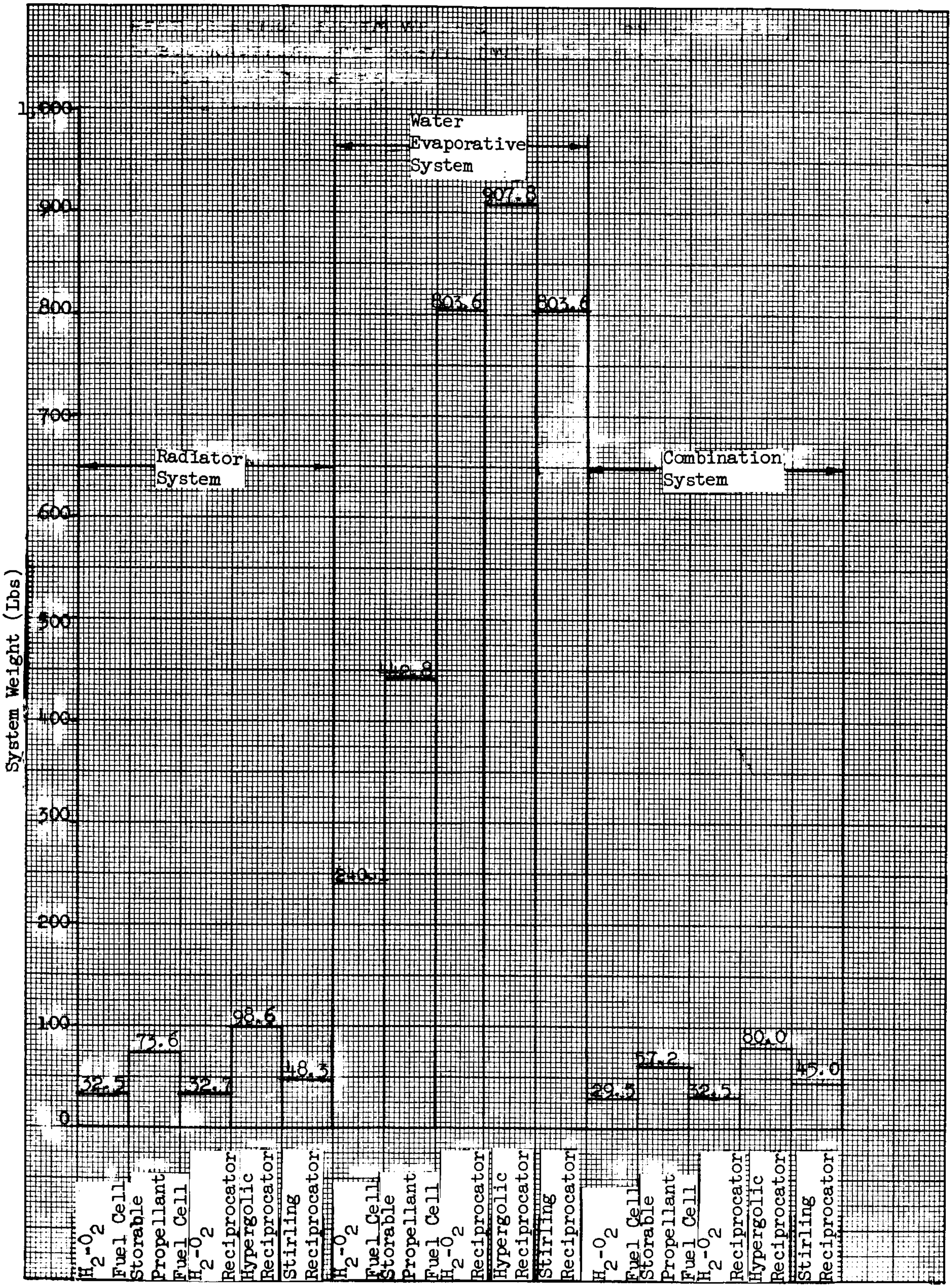


Figure A-7.- Heat rejection system weights (based on 0.55 lbs/ft^2)
300 nautical mile orbit
(Worst Case)

$\alpha/E = 0.20 \quad E = 0.90$

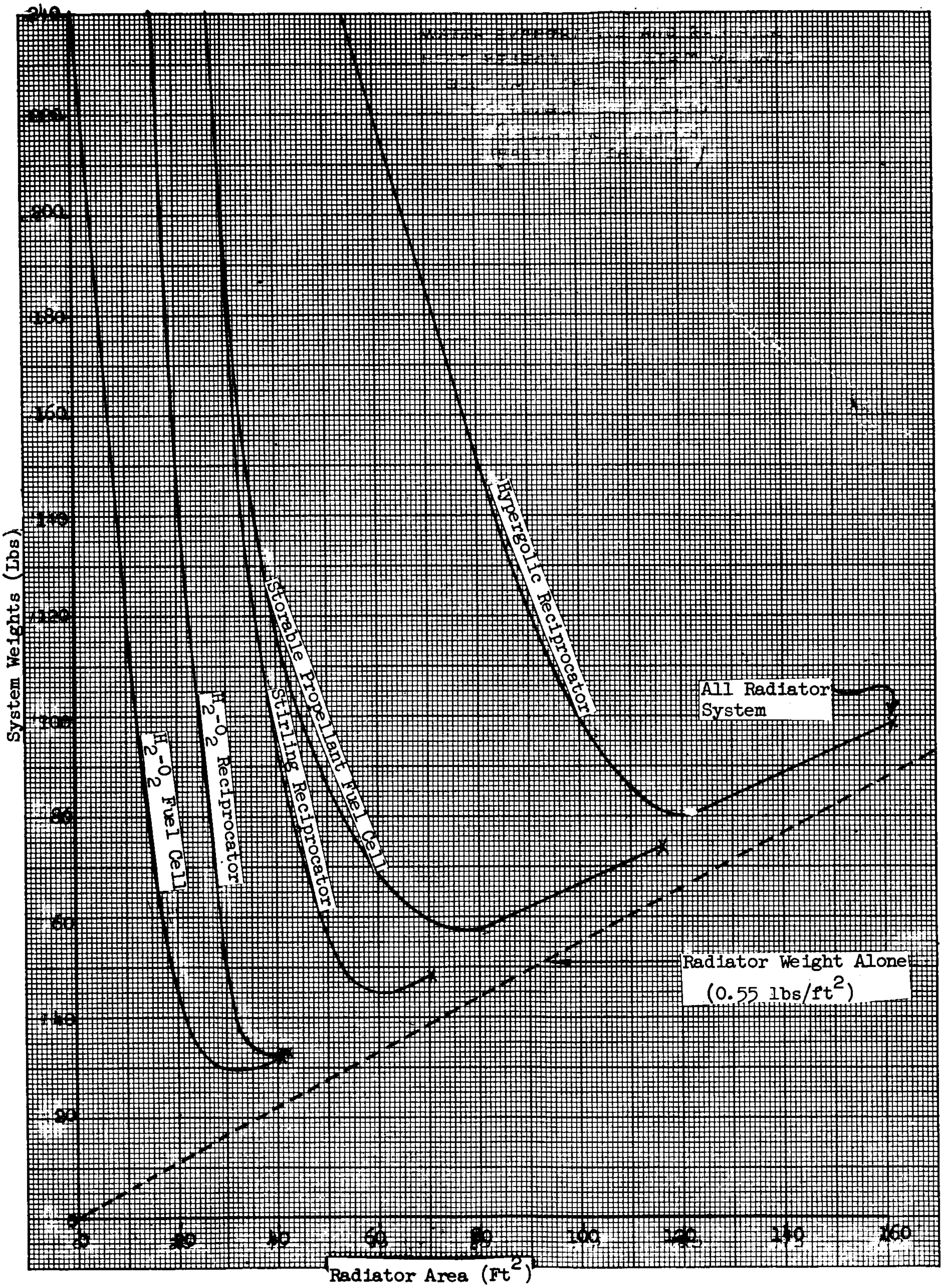


Figure A-8.- Water evaporative and radiator heat rejection system weights
300 nautical mile orbit

$\alpha/E = 0.20 \quad E = 0.90$

(Radiator Weights Based On Case II)

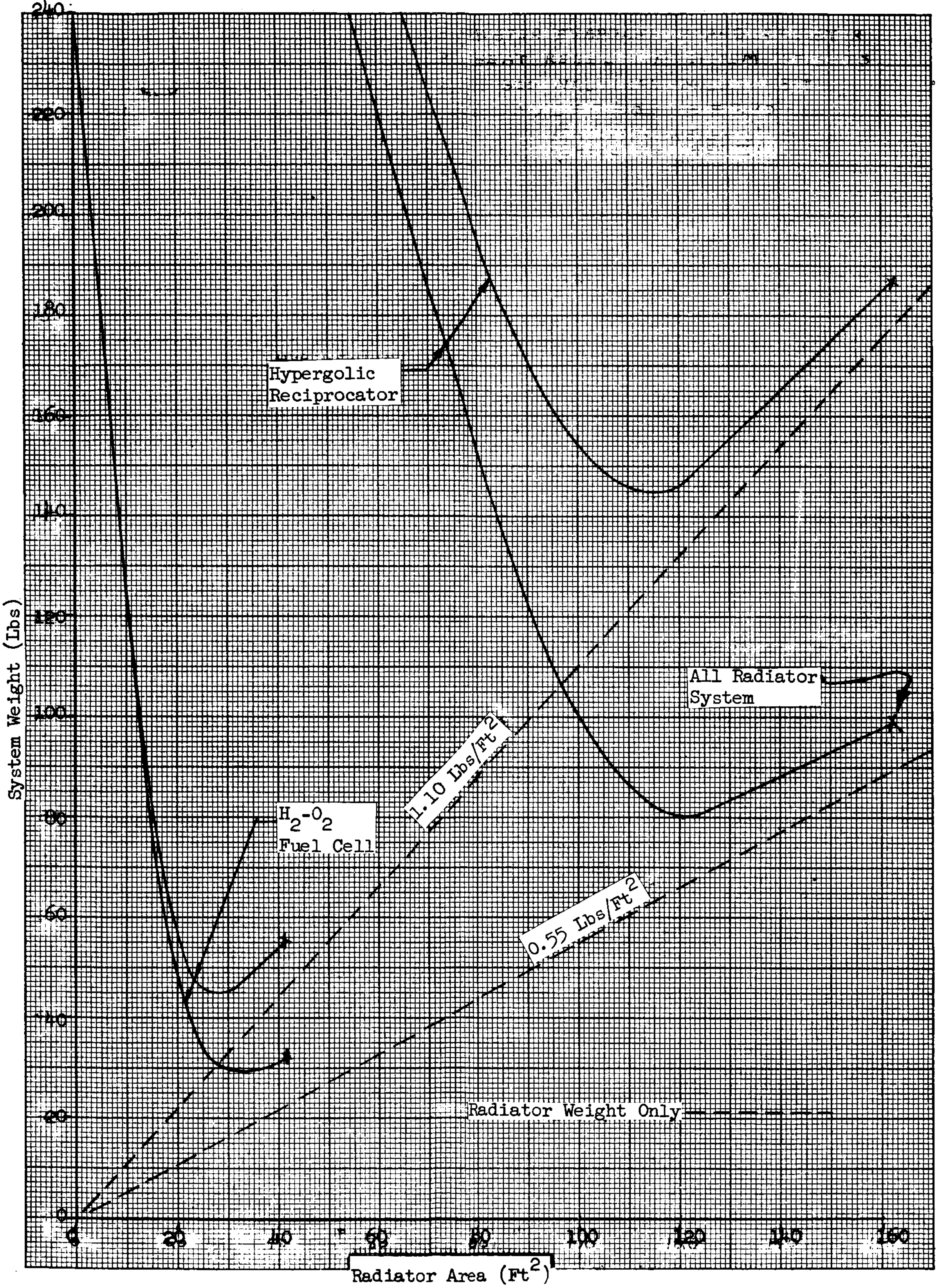


Figure A-9.- Water evaporative and radiator heat rejection system weights 300 nautical mile orbit

$\alpha/E = 0.20 \quad E = 0.90$

(Radiator Weights Based On Case II)

APPENDIX B

SYSTEM WEIGHTS

By: W. E. Simon
Propulsion and Power Division

APPENDIX B

SYSTEM WEIGHTS

Notes

a. Fuel cell calculations were based on current designs for the LEM (February 1964) which has a design power level of 900 watts. For a useful 2.1 kw, since the fuel cells must supply 2.7 kw gross, it was necessary to use three 900-watt units. Hence, in order to have a minimum of redundancy, it was necessary to use four fuel cell units in this preliminary study.

   More refined calculations would involve a fuel cell unit designed for 1.5 kw. Three of these would be used for this mission. At this time, however, no reliable data is available on a redesigned unit.

b. Because of the fact that four fuel cells were used in the fuel cell-battery combinations, it was thought necessary for the dynamic systems calculations to use three prime movers for each case, in order to provide an adequate redundancy. Later and more refined study may show that only two prime movers are necessary, each capable of providing 2.7 kw.

c. It must be remembered that these calculations are preliminary since precise system weights, configurations, and desired design power levels, are not available from the manufacturers for this specific mission. Besides, many of the systems for which calculations are presented have been built for other purposes or other missions, and the design power levels, as well as many other parameters, are far from optimum for this mission. In these cases the best weight estimates available were used.

d. It was assumed for the cooling calculations that the power system is at all times in a thermally conditioned module. Hence, for a chemical system, all waste heat which cannot be rejected by the combustion exhaust gases must be dissipated by a water boiler or a radiator.

e. For each case cooling calculations were carried out using (1) a water boiler, and (2) a radiator. Where the choice of a radiator or water boiler was not dependent upon mission constraints, the minimum weight incurred dictated the method of cooling. During launch and reentry it was assumed that a water boiler would be used, because aerodynamic heating would prohibit radiator operation.

f. No water boiler redundancy was added for any system, as this component is highly reliable.

1. Primary Batteries: (80 w.hr/lb)

Adapter module batteries		1,430 lbs
Crew module batteries		445
Hydraulic equipment		144
Power conditioning		113
	Total	2,132 lbs

2. H_2-O_2 Fuel Cells:

(a) Allis-Chalmers fuel cells

Adapter module batteries		238 lbs
Crew module batteries		445
Four energy conversion packages (ECP's)		260
Hydraulic equipment		144
Water boiler system		34
Radiator		136
Supercritical O_2 system (in adapter)		67
High pressure O_2 (in adapter)		118
High pressure H_2 (in adapter)		75
Power conditioning		113
	Total	1,653 lbs

(b) Allis-Chalmers fuel cells

Adapter module batteries		238 lbs
Crew module batteries		445
Four energy conversion packages		260
Hydraulic equipment		144
Water boiler system		34
Radiator		136
Subcritical O_2 system (in adapter)		57
Subcritical H_2 system (in adapter)		19
High pressure O_2 system (in adapter)		118
High pressure H_2 system (in adapter)		75
Power conditioning		113
	Total	1,639 lbs

(c) Allis-Chalmers fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator	136
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
Power conditioning	113
Total	2,010 lbs

(d) Allis-Chalmers fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator	136
Subcritical O_2 system (in adapter)	57
Subcritical H_2 system (in adapter)	19
Power conditioning	113
Total	1,995 lbs

(e) Allis-Chalmers fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator	136
High pressure O_2 system (in adapter)	257
High pressure H_2 system (in adapter)	152
Power conditioning	113
Total	1,779 lbs

(f) Allis-Chalmers fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator	136
High pressure O_2 system (in adapter)	138
High pressure H_2 system (in adapter)	78
Power conditioning	113
Total	2,135 lbs

(g) Allis-Chalmers fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator (mission)	136
Radiator (postlanding)	75
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
High pressure O_2 system (in adapter)	118
High pressure H_2 system (in adapter)	75
High pressure O_2 (in crew module)	52
High pressure H_2 (in crew module)	32
Power conditioning	113
Total	1,559 lbs

(h) Allis-Chalmers fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator (mission)	136
Radiator (postlanding)	75
Subcritical O_2 system (in adapter)	57
Subcritical H_2 system (in adapter)	19

(h) Allis-Chalmers fuel cells (Continued)

High pressure O_2 system (in adapter)	118 lbs
High pressure H_2 system (in adapter)	75
High pressure O_2 system (in crew module)	52
High pressure H_2 system (in crew module)	17
Power conditioning	113
Total	1,530 lbs

(i) Allis-Chalmers fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator (mission)	136
Radiator (postlanding)	75
High pressure O_2 system (in adapter)	257
High pressure H_2 system (in adapter)	152
High pressure O_2 system (in crew module)	52
High pressure H_2 system (in crew module)	32
Power conditioning	113
Total	1,685 lbs

(j) Allis-Chalmers fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator (mission)	136
Radiator (postlanding)	75
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
High pressure O_2 system (in crew module)	52
High pressure H_2 system (in crew module)	32
Power conditioning	113
Total	1,915 lbs

(k) Allis-Chalmers fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator (mission)	136
Radiator (postlanding)	75
Subcritical O_2 system (in adapter)	57
Subcritical H_2 system (in adapter)	19
Power conditioning	113
Total	1,901 lbs

(l) Allis-Chalmers fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	260
Hydraulic equipment	144
Water boiler system	34
Radiator (mission)	136
Radiator (postlanding)	75
High pressure O_2 system (in adapter)	138
High pressure H_2 system (in adapter)	78
High pressure O_2 system (in crew module)	52
High pressure H_2 system (in crew module)	32
Power conditioning	113
Total	2,041 lbs

(a) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	94
High pressure O_2 system (in adapter)	97
High pressure H_2 system (in adapter)	405
Power conditioning	113
Total	1,870 lbs

(b) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	80
High pressure O_2 system (in adapter)	97
High pressure H_2 system (in adapter)	405
Power conditioning	113
Total	1,847 lbs

(c) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	94
Power conditioning	113
Total	1,917 lbs

(d) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	80
Power conditioning	113
Total	1,894 lbs

(e) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
High pressure O_2 system (in adapter)	201
High pressure H_2 system (in adapter)	836
Power conditioning	113
Total	2,257 lbs

(f) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
High pressure O_2 system (in adapter)	114
High pressure H_2 system (in adapter)	474
Power conditioning	113
Total	2,357 lbs

(g) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	94
High pressure O_2 system (in adapter)	97
High pressure H_2 system (in adapter)	405
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	171
Power conditioning	113
Total	1,834 lbs

(h) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	80
High pressure O_2 system (in adapter)	97
High pressure H_2 system (in adapter)	405
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	171
Power conditioning	113
Total	1,811 lbs

(i) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
High pressure O_2 system (in adapter)	201
High pressure H_2 system (in adapter)	836
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	171
Power conditioning	113
Total	2,221 lbs

(j) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	94
Supercritical O_2 system (in crew module)	46

(j) Pratt and Whitney (open cycle) fuel cells (Continued)

Supercritical H_2 system (in crew module)	171 lbs
Power conditioning	113
Total	1,881 lbs

(k) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	80
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	171
Power conditioning	113
Total	1,858 lbs

(l) Pratt and Whitney (open cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	280
Hydraulic equipment	144
Cooling - none	
High pressure O_2 system (in adapter)	114
High pressure H_2 system (in adapter)	474
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	171
Power conditioning	113
Total	2,321 lbs

(a) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator	15

(a) Pratt and Whitney (closed cycle) fuel cells (Continued)

Supercritical O_2 system (in adapter)	54 lbs
Supercritical H_2 system (in adapter)	17
High pressure O_2 system (in adapter)	96
High pressure H_2 system (in adapter)	62
Power conditioning	113
Total	1,583 lbs

(b) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator	15
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	14
High pressure O_2 system (in adapter)	96
High pressure H_2 system (in adapter)	62
Power conditioning	113
Total	1,571 lbs

(c) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator	15
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	17
Power conditioning	113
Total	1,974 lbs

(d) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator	15
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	14
Power conditioning	113
Total	1,962 lbs

(e) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator	15
High pressure O_2 system (in adapter)	212
High pressure H_2 system (in adapter)	128
Power conditioning	113
Total	1,694 lbs

(f) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator	15
High pressure O_2 system (in adapter)	114
High pressure H_2 system (in adapter)	69
Power conditioning	113
Total	2,086 lbs

(g) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator (mission)	15
Radiator (postlanding)	4
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	17
High pressure O_2 system (in adapter)	96
High pressure H_2 system (in adapter)	62
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	28
Power conditioning	113
Total	1,408 lbs

(h) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator (mission)	15
Radiator (postlanding)	4
Subcritical O_2 system (in adapter)	45
Subcritical H_2 system (in adapter)	14
High pressure O_2 system (in adapter)	96
High pressure H_2 system (in adapter)	62
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	28
Power conditioning	113
Total	1,396 lbs

(i) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator (mission)	15
Radiator (postlanding)	4
High pressure O_2 system (in adapter)	212
High pressure H_2 system (in adapter)	128
High pressure O_2 system (in crew module)	45
High pressure H_2 system (in crew module)	28
Power conditioning	113
Total	1,518 lbs

(j) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator (mission)	15
Radiator (postlanding)	4
Supercritical O_2 system (in adapter)	54
Supercritical H_2 system (in adapter)	17
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	28
Power conditioning	113
Total	1,799 lbs

(k) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator (mission)	15
Radiator (postlanding)	4
Subcritical O_2 system (in adapter)	45

(k) Pratt and Whitney (closed cycle) fuel cells (Continued)

Subcritical H_2 system (in adapter)	14 lbs
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	28
Power conditioning	113
Total	1,787 lbs

(l) Pratt and Whitney (closed cycle) fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	380
Hydraulic equipment	144
Water boiler system	19
Radiator (mission)	15
Radiator (postlanding)	4
High pressure O_2 system (in adapter)	114
High pressure H_2 system (in adapter)	69
High pressure O_2 system (in crew module)	46
High pressure H_2 system (in crew module)	28
Power conditioning	113
Total	1,911 lbs

(a) General Electric fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator	324
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
High pressure O_2 system (in adapter)	120
High pressure H_2 system (in adapter)	71
Power conditioning	113
(Credit 7 lb of H_2O produced)	
Total	1,870 lbs

(b) General Electric fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator	324
Subcritical O_2 system (in adapter)	58
Subcritical H_2 system (in adapter)	19
High pressure O_2 system (in adapter)	120
High pressure H_2 system (in adapter)	71
Power conditioning	113
(Credit 7 lb of H_2O produced)	
Total	1,857 lbs

(c) General Electric fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator	324
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
Power conditioning	113
(Credit 7 lb of H_2O produced)	
Total	2,228 lbs

(d) General Electric fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator	324
Subcritical O_2 system (in adapter)	58
Subcritical H_2 system (in adapter)	19
Power conditioning	113
Credit 7 lb of H_2O produced)	
Total	2,215 lbs

(e) General Electric fuel cells

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator	324
High pressure O_2 system (in adapter)	259
High pressure H_2 system (in adapter)	154
Power conditioning (Credit 7 lb of H_2O produced)	113
Total	2,002 lbs

(f) General Electric fuel cells

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator	324
High pressure O_2 system (in adapter)	140
High pressure H_2 system (in adapter)	83
Power conditioning (Credit 7 lb of H_2O produced)	113
Total	2,361 lbs

(g) General Electric fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator (mission)	324
Radiator (postlanding)	108
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
High pressure O_2 system (in adapter)	120
High pressure H_2 system (in adapter)	71

(g) General Electric fuel cells (Continued)

High pressure O_2 system (in crew module)	56 lbs
High pressure H_2 system (in crew module)	33
Power conditioning (Credit 15 lbs of H_2O produced)	113
Total	1,806 lbs

(h) General Electric fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator (mission)	324
Radiator (postlanding)	108
Subcritical O_2 system (in adapter)	58
Subcritical H_2 system (in adapter)	19
High pressure O_2 system (in adapter)	120
High pressure H_2 system (in adapter)	71
High pressure O_2 system (in crew module)	56
High pressure H_2 system (in crew module)	33
Power conditioning (Credit 15 lbs of H_2O produced)	113
Total	1,793 lbs

(i) General Electric fuel cells

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator (mission)	324
Radiator (postlanding)	108
High pressure O_2 system (in adapter)	259
High pressure H_2 system (in adapter)	154
High pressure O_2 system (in crew module)	48

(i) General Electric fuel cells (Continued)

High pressure H_2 system (in crew module)	29 lbs
Power conditioning (Credit 15 lbs of H_2O produced)	113
Total	1,926 lbs

(j) General Electric fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator (mission)	324
Radiator (postlanding)	108
Supercritical O_2 system (in adapter)	67
Supercritical H_2 system (in adapter)	23
High pressure O_2 system (in crew module)	56
High pressure H_2 system (in crew module)	33
Power conditioning (Credit 15 lbs of H_2O produced)	113
Total	2,164 lbs

(k) General Electric fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator (mission)	324
Radiator (postlanding)	108
Subcritical O_2 system (in adapter)	58
Subcritical H_2 system (in adapter)	19
High pressure O_2 system (in crew module)	56
High pressure H_2 system (in crew module)	33
Power conditioning (Credit 15 lbs of H_2O produced)	113
Total	2,151 lbs

(1) General Electric fuel cells

Adapter module batteries	787 lbs
Crew module batteries	192
Four energy conversion packages	288
Hydraulic equipment	144
Water boiler system	44
Radiator (mission)	324
Radiator (postlanding)	108
High pressure O_2 system (in adapter)	144
High pressure H_2 system (in adapter)	84
High pressure O_2 system (in crew module)	56
High pressure H_2 system (in crew module)	33
Power conditioning (Credit 15 lbs H_2O produced)	113
Total	2,302 lbs

3. Storable fuel cell

(a)

Adapter module batteries	787 lbs
Crew module batteries	445
Four energy conversion packages	286
Hydraulic equipment	144
Water boiler system	50
Cooling equipment	40
Subcritical O_2 system (in adapter)	73
N_2H_4 system (in adapter)	72
He pressurization system	2
Power conditioning	113
Total	2,012 lbs

(b)

Adapter module batteries	238 lbs
Crew module batteries	445
Four energy conversion packages	286
Hydraulic equipment	144
Water boiler system	50
Cooling equipment	40
Subcritical O_2 system (in adapter)	73
High pressure O_2 system (in adapter)	149
N_2H_4 system (in adapter)	130
He pressurization system	4
Power conditioning	113
Total	1,672 lbs

(c)

Adapter module batteries	238 lbs
Crew module batteries	192
Four energy conversion packages	286
Hydraulic equipment	144
Water boiler system	50
Cooling equipment	40
Subcritical O_2 system (in adapter)	73
High pressure O_2 system (in adapter)	149
N_2H_4 system (in adapter)	130
High pressure O_2 system (in crew module)	69
N_2H_4 system (in crew module)	65
He pressurization system	5
Power conditioning	113
Total	1,554 lbs

(d)

Adapter module batteries	881 lbs
Crew module batteries	192
Four energy conversion packages	286
Hydraulic equipment	144
Water boiler system	50
Cooling equipment	40
High pressure O_2 system (in adapter)	149
N_2H_4 system (in adapter)	63
High pressure O_2 system (in crew module)	69
N_2H_4 system (in crew module)	65
He pressurization system	3
Power conditioning	113
Total	2,055 lbs

4. Storable monopropellant turbine

(a)

Adapter module batteries	238 lbs
Crew module batteries	445
Three prime movers	256
Hydraulic equipment	144
Water boiler system	95
Radiator	237
Hydrazine	638
Tankage	108
N_2O_4 and tankage (for starting)	15
He pressurization	22
Power conditioning	96
Total	2,294 lbs

(b)

Adapter module batteries		787 lbs
Crew module batteries		445
Three prime movers		256
Hydraulic equipment		144
Water boiler system		95
Radiator		237
Hydrazine		345
Tankage		60
N_2O_4 and tankage (for starting)		15
He pressurization		12
Power conditioning		96
	Total	2,492 lbs

(c)

Adapter module batteries		238 lbs
Crew module batteries		192
Three prime movers		256
Hydraulic equipment		144
Water boiler system		95
Radiator (mission)		237
Radiator (postlanding)		137
Hydrazine (in adapter)		638
Tankage (in adapter)		108
Hydrazine (in crew module)		136
Tankage (in crew module)		27
N_2O_4 and tankage (for starting)		30
He pressurization		27
Power conditioning		96
	Total	2,361 lbs

(d)

Adapter module batteries		882 lbs
Crew module batteries		192
Three prime movers		256
Hydraulic equipment		144
Radiator (mission)		237
Radiator (postlanding)		137
Hydrazine (in adapter)		294
Tankage (in adapter)		62
Hydrazine (in crew module)		136
Tankage (in crew module)		27
N_2O_4 and tankage (for starting)		30
He pressurization		15
Power conditioning		96
	Total	2,508 lbs

(e)

Three prime movers	465 lbs
Water boiler systems (launch)	95
Water boiler system (reentry)	40
Water boiler system (pre-retro)	208
Radiator	237
Hydrazine (in adapter)	767
Hydrazine (in crew module)	239
Tankage (in adapter)	129
Tankage (in crew module)	43
N_2O_4 and tankage (for starting)	15
He pressurization	34
Power conditioning	96
Total	2,368 lbs

5. Storable bipropellant (intermittent) turbine

(a)

Adapter module batteries	238 lbs
Crew module batteries	445
Three prime movers	342
Hydraulic equipment	144
Water boiler system	11
Radiator system	101
Aerozine-50	388
Aerozine-50 tankage	68
N_2O_4	233
N_2O_4 tankage	31
He pressurization	19
Power conditioning	133
Total	2,153 lbs

(b)

Adapter module batteries	787 lbs
Crew module batteries	445
Three prime movers	342
Hydraulic equipment	144
Water boiler system	11
Radiator system	101
Aerozine-50	209
Aerozine-50 tankage	39
N_2O_4	126
N_2O_4 tankage	19
He pressurization	10
Power conditioning	133
Total	2,366 lbs

(c)

Adapter module batteries	238 lbs
Crew module batteries	192
Three prime movers	342
Hydraulic equipment	144
Water boiler system	11
Radiator system (mission)	101
Radiator system (postlanding)	67
Aerozine-50 (in adapter)	388
Aerozine-50 tankage (in adapter)	68
N_2O_4 (in adapter)	233
N_2O_4 tankage (in adapter)	31
Aerozine-50 (in crew module)	93
Aerozine-50 tankage (in crew module)	20
N_2O_4 (in crew module)	50
N_2O_4 (in crew module)	10
He pressure	24
Power conditioning	133
Total	2,145 lbs

(d)

Adapter module batteries	882 lbs
Crew module batteries	192
Three prime movers	342
Hydraulic equipment	144
Water boiler system	11
Radiator system (mission)	101
Radiator system (postlanding)	67
Aerozine-50 (in adapter)	178
Aerozine-50 tankage (in adapter)	34
N_2O_4 (in adapter)	107
N_2O_4 tankage (in adapter)	17
Aerozine-50 (in crew module)	93
Aerozine-50 tankage (in crew module)	20
N_2O_4 (in crew module)	50
N_2O_4 tankage (in crew module)	10
He pressurization	14
Power conditioning	133
Total	2,395 lbs

(e)	Three prime movers	360 lbs
	Water boiler system (launch)	11
	Water boiler system (reentry)	16
	Water boiler system (pre-retro)	30
	Radiator	101
	Aerozine-50 (in adapter)	465
	Aerozine-50 tankage (in adapter)	81
	N_2O_4 (in adapter)	279
	N_2O_4 tankage (in adapter)	37
	Aerozine-50 (in crew module)	144
	Aerozine-50 tankage (in crew module)	28
	N_2O_4 (in crew module)	87
	N_2O_4 tankage (in crew module)	15
	He pressurization	29
	Power conditioning	133
	Total	1,816 lbs

6. Storable bipropellant (hypergolic) reciprocator

(a)	Adapter module batteries	238 lbs
	Crew module batteries	445
	Three prime movers	231
	Hydraulic equipment	144
	Water boiler system	64
	Radiator	131
	Aerozine-50 (in adapter)	136
	Aerozine-50 tankage (in adapter)	27
	N_2O_4 (in adapter)	246
	N_2O_4 tankage (in adapter)	33
	He pressurization	11
	Power conditioning	113
	Total	1,819 lbs

(b)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	231
	Hydraulic equipment	144
	Water boiler system	64
	Radiator	131
	Aerozine-50 (in adapter)	73
	Aerozine-50 tankage (in adapter)	17
	N_2O_4 (in adapter)	133
	N_2O_4 tankage (in adapter)	20

(b) Continued

He pressurization		6 lbs
Power conditioning		113
	Total	2,164 lbs

(c)

Adapter module batteries		238 lbs
Crew module batteries		192
Three prime movers		231
Hydraulic equipment		144
Water boiler system		64
Radiator (mission)		131
Radiator (postlanding)		122
Aerozine-50 (in adapter)		136
Aerozine-50 tankage (in adapter)		27
N_2O_4 (in adapter)		246
N_2O_4 tankage (in adapter)		33
Aerozine-50 (in crew module)		29
Aerozine-50 tankage (in crew module)		10
N_2O_4 (in crew module)		53
N_2O_4 (in crew module)		11
He pressurization		13
Power conditioning		113
	Total	1,793 lbs

(d)

Adapter module batteries		882 lbs
Crew module batteries		192
Three prime movers		231
Hydraulic equipment		144
Radiator (mission)		131
Radiator (postlanding)		122
Aerozine-50 (in adapter)		63
Aerozine-50 tankage (in adapter)		15
N_2O_4 (in adapter)		113
N_2O_4 tankage (in adapter)		18
Aerozine-50 (in crew module)		29
Aerozine-50 tankage (in crew module)		10
N_2O_4 (in crew module)		53
N_2O_4 tankage (in crew module)		11
He pressurization		7
Power conditioning		113
	Total	2,134 lbs

(e)

Three prime movers	441 lbs
Water boiler system (launch)	64
Water boiler system (reentry)	37
Water boiler system (pre-retro)	140
Radiator	131
Aerozine-50 (in adapter)	164
Aerozine-50 tankage (in adapter)	32
N_2O_4 (in adapter)	294
N_2O_4 tankage (in adapter)	38
Aerozine-50 (in crew module)	51
Aerozine-50 tankage (in crew module)	13
N_2O_4 (in crew module)	92
N_2O_4 tankage (in crew module)	15
He pressurization	17
Power conditioning	113
Total	1,642 lbs

7. H_2-O_2 receiprocator

(a)

Adapter module batteries	238 lbs
Crew module batteries	445
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator	131
Supercritical O_2 system (in adapter)	102
Supercritical H_2 system (in adapter)	110
High pressure O_2 system (in adapter)	184
High pressure H_2 system (in adapter)	437
Power conditioning	96
Total	2,260 lbs

(b)

Adapter module batteries	238 lbs
Crew module batteries	445
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator	131
Subcritical O_2 system (in adapter)	87
Subcritical H_2 system (in adapter)	91

(b)	Continued	
	High pressure O_2 system (in adapter)	184 lbs
	High pressure H_2 system (in adapter)	437
	Power conditioning	96
	Total	2,226 lbs
(c)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	309
	Hydraulic equipment	144
	Water boiler system	64
	Radiator	131
	Supercritical O_2 system (in adapter)	102
	Supercritical H_2 system (in adapter)	110
	Power conditioning	96
	Total	2,188 lbs
(d)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	309
	Hydraulic equipment	144
	Water boiler system	64
	Radiator	131
	Subcritical O_2 system (in adapter)	87
	Subcritical H_2 system (in adapter)	91
	Power conditioning	96
	Total	2,154 lbs
(e)	Adapter module batteries	238 lbs
	Crew module batteries	445
	Three prime movers	309
	Hydraulic equipment	144
	Water boiler system	64
	Radiator	131
	High pressure O_2 system (in adapter)	400
	High pressure H_2 system (in adapter)	951
	Power conditioning	96
	Total	2,778 lbs

(f)

Adapter module batteries	787 lbs
Crew module batteries	445
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator	131
High pressure O_2 system (in adapter)	217
High pressure H_2 system (in adapter)	513
Power conditioning	96
Total	2,706 lbs

(g)

Adapter module batteries	238 lbs
Crew module batteries	192
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator (mission)	131
Radiator (postlanding)	122
Supercritical O_2 system (in adapter)	102
Supercritical H_2 system (in adapter)	110
High pressure O_2 system (in adapter)	184
High pressure H_2 system (in adapter)	437
High pressure O_2 system (in crew module)	86
High pressure H_2 system (in crew module	201
Power conditioning	96
Total	2,416 lbs

(h)

Adapter module batteries	238 lbs
Crew module batteries	192
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator (mission)	131
Radiator (postlanding)	122
Subcritical O_2 system (in adapter)	87
Subcritical H_2 system (in adapter)	91
High pressure O_2 system (in adapter)	184
High pressure H_2 system (in adapter)	437
High pressure O_2 system (in crew module)	86
High pressure H_2 system (in crew module)	201
Power conditioning	96
Total	2,382 lbs

(i)

Adapter module batteries	238 lbs
Crew module batteries	192
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator (mission)	131
Radiator (postlanding)	122
High pressure O_2 system (in adapter)	400
High pressure H_2 system (in adapter)	951
High pressure O_2 system (in crew module)	86
High pressure H_2 system (in crew module)	201
Power conditioning	96
Total	2,934 lbs

(j)

Adapter module batteries	787 lbs
Crew module batteries	192
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator (mission)	131
Radiator (postlanding)	122
Supercritical O_2 system (in adapter)	102
Supercritical H_2 system (in adapter)	110
High pressure O_2 system (in crew module)	86
High pressure H_2 system (in crew module)	201
Power conditioning	96
Total	2,344 lbs

(k)

Adapter module batteries	787 lbs
Crew module batteries	192
Three prime movers	309
Hydraulic equipment	144
Water boiler system	64
Radiator (mission)	131
Radiator (postlanding)	122
Subcritical O_2 system (in adapter)	87
Subcritical H_2 system (in adapter)	91
High pressure O_2 system (in crew module)	86
High pressure H_2 system (in crew module)	201
Power conditioning	96
Total	2,310 lbs

(1)	Adapter module batteries	787 lbs
	Crew module batteries	192
	Three prime movers	309
	Hydraulic equipment	144
	Water boiler system	64
	Radiator (mission)	131
	Radiator (postlanding)	122
	High pressure O_2 system (in adapter)	217
	High pressure H_2 system (in adapter)	513
	High pressure O_2 system (in crew module)	86
	High pressure H_2 system (in crew module)	201
	Power conditioning	96
	Total	2,862 lbs

8. H_2-O_2 Stirling cycle reciprocator

(a)	Adapter module batteries	238 lbs
	Crew module batteries	445
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator	171
	Supercritical O_2 system (in adapter)	212
	Supercritical H_2 system (in adapter)	61
	High pressure O_2 system (in adapter)	390
	High pressure H_2 system (in adapter)	227
	Power conditioning	96
	Total	2,630 lbs

(b)	Adapter module batteries	238 lbs
	Crew module batteries	445
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator	171
	Subcritical O_2 system (in adapter)	179
	Subcritical H_2 system (in adapter)	50
	High pressure O_2 system (in adapter)	390
	High pressure H_2 system (in adapter)	227
	Power conditioning	96
	Total	2,586 lbs

(c)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator	171
	Supercritical O_2 system (in adapter)	212
	Supercritical H_2 system (in adapter)	61
	Power conditioning	96
	Total	2,562 lbs
(d)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator	171
	Subcritical O_2 system (in adapter)	179
	Subcritical H_2 system (in adapter)	50
	Power conditioning	96
	Total	2,518 lbs
(e)	Adapter module batteries	238 lbs
	Crew module batteries	445
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator	171
	High pressure O_2 system (in adapter)	844
	High pressure H_2 system (in adapter)	500
	Power conditioning	96
	Total	3,084 lbs
(f)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	1,531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator	171
	High pressure O_2 system (in adapter)	457
	High pressure H_2 system (in adapter)	270
	Power conditioning	96
	Total	3,016 lbs

(g)

Adapter module batteries	238 lbs
Crew module batteries	192
Three prime movers	531
Hydraulic equipment	144
Water boiler system	115
Radiator (mission)	171
Radiator (postlanding)	168
Supercritical O_2 system (in adapter)	212
Supercritical H_2 system (in adapter)	61
High pressure O_2 system (in adapter)	390
High pressure H_2 system (in adapter)	227
High pressure O_2 system (in crew module)	180
High pressure H_2 system (in crew module)	106
Power conditioning	96
Total	2,831 lbs

(h)

Adapter module batteries	238 lbs
Crew module batteries	192
Three prime movers	531
Hydraulic equipment	144
Water boiler system	115
Radiator (mission)	171
Radiator (postlanding)	168
Subcritical O_2 system (in adapter)	179
Subcritical H_2 system (in adapter)	50
High pressure O_2 system (in adapter)	390
High pressure H_2 system (in adapter)	227
High pressure O_2 system (in crew module)	180
High pressure H_2 system (in crew module)	106
Power conditioning	96
Total	2,787 lbs

(i)	Adapter module batteries	238 lbs
	Crew module batteries	192
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator (mission)	171
	Radiator (postlanding)	168
	High pressure O_2 (in adapter)	844
	High pressure H_2 (in adapter)	500
	High pressure O_2 (in adapter)	180
	High pressure H_2 (in adapter)	106
	Power conditioning	96
	Total	3,285 lbs

(j)	Adapter module batteries	787 lbs
	Crew module batteries	192
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator (mission)	171
	Radiator (postlanding)	168
	Supercritical O_2 systems (in adapter)	212
	Supercritical H_2 systems (in adapter)	61
	High pressure O_2 system (in adapter)	180
	High pressure H_2 systems (in adapter)	106
	Power conditioning	96
	Total	2,763 lbs

(k)	Adapter module batteries	787 lbs
	Crew module batteries	192
	Three prime movers	531
	Hydraulic equipment	144
	Water boiler system	115
	Radiator (mission)	171
	Radiator (postlanding)	168
	Subcritical O_2 system (in adapter)	179
	Subcritical H_2 system (in adapter)	50
	High pressure O_2 system (in crew module)	180
	High pressure H_2 system (in crew module)	106
	Power conditioning	96
	Total	2,719 lbs

(1)

Adapter module batteries	787 lbs
Crew module batteries	192
Three prime movers	531
Hydraulic equipment	144
Water boiler system	115
Radiator (mission)	171
Radiator (postlanding)	168
High pressure O_2 system (in adapter)	457
High pressure H_2 system (in adapter)	270
High pressure O_2 system (in crew module)	180
High pressure H_2 system (in crew module)	106
Power conditioning	96
Total	3,217 lbs

9. H_2-O_2 Brayton cycle turbine

(a)

Adapter module batteries	238 lbs
Crew module batteries	445
Three prime movers	261
Hydraulic equipment	144
Water boiler system	146
Radiator	194
Supercritical O_2 systems (in adapter)	155
Supercritical H_2 systems (in adapter)	46
High pressure O_2 systems (in adapter)	285
High pressure H_2 systems (in adapter)	171
Power conditioning	133
Total	2,218 lbs

(b)

Adapter module batteries	238 lbs
Crew module batteries	445
Three prime movers	261
Hydraulic equipment	144
Water boiler system	146
Radiator	194
Subcritical O_2 systems (in adapter)	131
Subcritical H_2 systems (in adapter)	38
High pressure O_2 systems (in adapter)	285
High pressure H_2 systems (in adapter)	171
Power conditioning	133
Total	2,186 lbs

(c)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator	194
	Supercritical O_2 system (in adapter)	155
	Supercritical H_2 system (in adapter)	46
	Power conditioning	133
	Total	2,311 lbs
(d)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator	194
	Subcritical O_2 systems (in adapter)	131
	Subcritical H_2 systems (in adapter)	38
	Power conditioning	133
	Total	2,279 lbs
(e)	Adapter module batteries	238 lbs
	Crew module batteries	445
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator	194
	High pressure O_2 systems (in adapter)	615
	High pressure H_2 systems (in adapter)	370
	Power conditioning	133
	Total	2,546 lbs
(f)	Adapter module batteries	787 lbs
	Crew module batteries	445
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator	194
	High pressure O_2 systems (in adapter)	333
	High pressure H_2 systems (in adapter)	199
	Power conditioning	133
	Total	2,642 lbs

(g)	Adapter module batteries	238 lbs
	Crew module batteries	192
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator (mission)	194
	Radiator (postlanding)	172
	Supercritical O_2 system (in adapter)	155
	Supercritical H_2 system (in adapter)	46
	High pressure O_2 systems (in adapter)	285
	High pressure H_2 systems (in adapter)	171
	High pressure O_2 systems (in crew module)	132
	High pressure H_2 systems (in crew module)	85
	Power conditioning	133
	Total	2,354 lbs

(h)	Adapter module batteries	238 lbs
	Crew module batteries	192
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator (mission)	194
	Radiator (postlanding)	172
	Subcritical O_2 system (in adapter)	131
	Subcritical H_2 system (in adapter)	38
	High pressure O_2 system (in adapter)	285
	High pressure H_2 system (in adapter)	171
	High pressure O_2 system (in crew module)	132
	High pressure H_2 system (in crew module)	85
	Power conditioning	133
	Total	2,322 lbs

(i)	Adapter module batteries	238 lbs
	Crew module batteries	192
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator (mission)	194
	Radiator (postlanding)	172
	High pressure O_2 system (in adapter)	615

(i) Continued

High pressure H_2 system (in adapter)		370 lbs
High pressure O_2 system (in crew module)		132
High pressure H_2 system (in crew module)		85
Power conditioning		133
	Total	2,682 lbs

(j)

Adapter module batteries		787 lbs
Crew module batteries		192
Three prime movers		261
Hydraulic equipment		144
Water boiler system		146
Radiator (mission)		194
Radiator (postlanding)		172
Supercritical O_2 system (in adapter)		155
Supercritical H_2 system (in adapter)		46
High pressure O_2 system (in crew module)		132
High pressure H_2 system (in crew module)		85
Power conditioning		133
	Total	2,447 lbs

(k)

Adapter module batteries		787 lbs
Crew module batteries		192
Three prime movers		261
Hydraulic equipment		144
Water boiler system		146
Radiator (mission)		194
Radiator (postlanding)		172
Subcritical O_2 system (in adapter)		131
Subcritical H_2 system (in adapter)		38
High pressure O_2 system (in crew module)		132
High pressure H_2 system (in crew module)		85
Power conditioning		133
	Total	2,415 lbs

(l)	Adapter module batteries	787 lbs
	Crew module batteries	192
	Three prime movers	261
	Hydraulic equipment	144
	Water boiler system	146
	Radiator (mission)	194
	Radiator (postlanding)	172
	High pressure O_2 system (in adapter)	333
	High pressure H_2 system (in adapter)	199
	High pressure O_2 system (in crew module)	132
	High pressure H_2 system (in crew module)	85
	Power conditioning	133
	Total	2,778 lbs
(m)	Three prime movers	348 lbs
	Water boiler system (launch)	146
	Water boiler system (reentry)	49
	Water boiler system (pre-retro)	187
	Radiator	194
	Supercritical O_2 system (in adapter)	340
	Supercritical H_2 system (in adapter)	94
	High pressure O_2 system (in crew module)	230
	High pressure H_2 system (in crew module)	133
	Power conditioning	133
	Total	1,854 lbs
(n)	Three prime movers	348 lbs
	Water boiler system (launch)	146
	Water boiler system (reentry)	49
	Water boiler system (pre-retro)	187
	Radiator	194
	Subcritical O_2 system (in adapter)	288
	Subcritical H_2 system (in adapter)	70
	High pressure O_2 system (in crew module)	230
	High pressure H_2 system (in crew module)	133
	Power conditioning	133
	Total	1,778 lbs

10. Isotope - Stirling cycle reciprocator

Adapter module batteries		238 lbs
Crew module batteries		192
Three prime movers		657
Heat exchanger (includes isotopes*)		550
Water boiler system (launch)		314
Radiator		513
Power conditioning		96
	Total	2,560 lbs

* Polonium - 210

11. Isotope - Brayton cycle turbine

Adapter module batteries		238 lbs
Crew module batteries		192
Three prime movers		162
Heat exchanger (includes Po-210)		600
Water boiler system (launch)		432
Radiator		548
Power conditioning		133
	Total	2,305 lbs

12. Isotope - Rankine cycle turbine

Adapter module batteries		238 lbs
Crew module batteries		192
Three prime movers		429
Heat exchangers (includes Po-210)		700
Water boiler system (launch)		819
Radiator		426
Power conditioning		133
	Total	2,937 lbs